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VOL. XLV

OCTOBER-DECEMBER, 1906.

No. 184.

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THE PARAGENESIS OF THE MINERALS IN THE GLAUCOPHANE-BEARING ROCKS OF CALIFORNIA.

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*(Read October 5, 1906.)*

OCCURRENCE OF GLAUCOPHANE-BEARING ROCKS IN CALIFORNIA.

Glaucophane-bearing rocks are widely distributed in the Coast Ranges of California, in the Franciscan series, commonly associated with serpentine (altered peridotite). The rocks that contain glaucophane are classed together because of the occurrence of this mineral, but they are of widely different characters and origin. It is likely, however, that they were all affected by the same sort of metamorphism, although the writers that have discussed these rocks are by no means agreed as to whether this metamorphism was due to contact or to dynamic action.

No glaucophane is developed in the extensive series of mica schists along the granite contacts of the Coast Ranges, where micaceous and hornblendic gneissic and schistose rocks are abundant. And yet those schists are not essentially different in chemical nature from the glaucophane rocks. In the Franciscan series, on the other hand, glaucophane is abundant in altered rocks ranging in character

from acid quartzites and diorites to very basic gabbros and diabases. It is, therefore, clear that the chemical nature of the altered rocks can have had little influence on the formation of the glaucophane, though of course it decided the petrographic character.

The glaucophanes in the Coast Ranges of California are always products of metamorphism, and never of crystallization out of a magma. And while they are found in altered igneous rocks just as often as in altered sedimentaries, they are always secondary in both. It is thus clear that the petrographic character can have had just as little influence as the chemical constitution on the formation of glaucophane. It is true that the sedimentary rocks altered to glaucophane schists are all acid, with the exception of tuffs, and that the igneous rocks that have had glaucophane developed in them are mostly basic. But then non-calcareous sediments are usually acid, on account of the predominance of quartz sand; and acid intrusive rocks are rare in the Franciscan series.

Ransome<sup>1</sup> has shown that glaucophane has been developed on a small scale in chert at the contact with serpentine, and with metabasalts or "fourchites." There are, however, in the Coast Ranges extensive glaucophane schist masses near which neither serpentine nor metabasalt has been found. And often where such schists are near serpentine they are in much greater masses than the igneous rocks to which the metamorphism might be ascribed. From this it would seem illogical to assume that the formation of glaucophane schists is due in every case to contact with basic intrusive rocks. There are also numerous contacts of such basic intrusives with sediments where no schists have been formed.

On the other hand, we might assume that dynamic metamorphism has been the cause of the formation of the glaucophane schists, for the Franciscan series is usually crushed, and zones of shearing are common in it. But while the glaucophane rocks are extensively developed for several hundred miles in the Coast Ranges, from Oregon to San Diego, there are no continuous masses of schists. Thus the cause of metamorphism can hardly have been regional. And it is hard to see how this agency can have been intermittent or local in its action, since the rocks of the Franciscan series are

<sup>1</sup> "Geology of Angel Island," *Bull. Dept. Geol. Univ. Calif.*, Vol. I., p. 223.

crushed and sheared almost everywhere, even where no glaucophane has been developed in them. Yet, in a sense, the phenomenon is regional, that is, confined to a petrographic region, or, more properly, a region of one sort of geologic activity.

Neither in the Rocky Mountain, the Lake Superior, nor in the Appalachian region, are glaucophane schists developed; although amphibole and garnet schists are common. Nor yet in the Sierra Nevada of California, where extensive schist masses, both of dynamic and of contact origin, are common, is any glaucophane schist known. And there, too, extensive masses of peridotites occur, and altered sediments of the same chemical character as in the Coast Ranges, but of totally different petrographic character. Altered quartzites are abundant in the Sierra Nevada, also altered clay shales and altered diabase tuffs. But the quartzites have been changed to sericite schists, the clay shales to andalusite schists, and the diabase tuffs and the peridotites to amphibolites, all without glaucophane. And, what is more puzzling, the metamorphism in the Sierra Nevada and in the Coast Ranges seem to have been contemporaneous.

#### MINERALS OF THE GLAUCOPHANE-BEARING ROCKS.

##### *Primary Minerals.*

Under this head are treated those minerals that were present in the original rock, and have remained unaltered. Feldspars were important constituents of the original rocks, both igneous and sedimentary, but they have rarely resisted the readjustment consequent upon metamorphism. In a quartz diorite from Oak Ridge, about five miles east of Calaveras Valley, Santa Clara County, the original oligoclase is largely intact, though decomposed in spots where secondary glaucophane (crossite) and lawsonite have been formed.

The original labradorites of the pseudodiorites and the pseudodiabases (altered diabases) of Sulphur Bank and other localities are partly preserved as such, although usually they are entirely decomposed. In general, the feldspars have been the first minerals altered, as can be seen in the pseudodiabases, where often the hornblende or the augite is unaltered, and the feldspars are changed to a saussuritic mass.

Original hornblende has been observed in the altered quartz diorite of the Oak Ridge, where it shows all the characters of the titaniferous kataphorite. This has been decomposed around the borders, with the addition of soda to form glaucophane (crossite), and the setting free of titanium to form leucoxene, and titanite. Most of the hornblende of the pseudodiorites and pseudodiabases is not original in the strictest sense, for it is largely uralite after augite, but it was already present before the metamorphism which later formed epidote and glaucophane in these rocks.

Quartz is present as an undoubted original constituent only in the quartz diorite, but much of the quartz in the siliceous glaucophane schists may be original, since there is no criterion by which the original granular quartz may be distinguished from the same mineral when recrystallized.

Original augite is present only in the pseudodiabases and pseudodiorites, and a few greenstones, where the metamorphism has not gone very far.

#### *Secondary Minerals.*

Of all the constituents of the metamorphic rocks of the Coast Ranges of California glaucophane is the most characteristic. There are probably several varieties of it, but at present it is not practicable to separate them. In all the true glaucophanes in these rocks there are certain general characteristics that distinguish them. The vertical axis is the axis of least elasticity, the extinction angle of  $c \wedge c$  is small, ranging from  $5^\circ$  to  $14^\circ$ . The character of the double refraction is always negative, and the plane of the optic axes lies in the plane of symmetry. The angle of the optic axes in some varieties is so small that the mineral is almost uniaxial, in others the angle is moderately wide. The pleochroism is always strong, the light vibrating parallel to  $a$  being pale yellowish, that parallel to  $b$  deep violet, and that parallel to  $c$  intense sky blue. The crystal faces are extremely simple, only three distinct forms being seen, the orthopinacoid (100), the prism (110), and the clinopinacoid (010). The crystals are usually in long prisms after (110) rarely showing the other faces.

This mineral is equally at home in the acid quartzites, altered diorites, diabases and gabbros, so the acidity or basicity of the

original rock has had no influence on its formation. Naturally glaucophane is more abundant in the basic metamorphics, where there was more iron and soda necessary for its genesis.

A rare variety of glaucophane has been described by Palache<sup>1</sup> from the Coast Ranges under the name of crossite. This differs from common glaucophane chiefly in the orientation of the axes of elasticity, the plane of the optic axes being transverse. The pleochroism is the same as that of glaucophane, except that the colors are more intense. The polarization colors appear to be lower than those of glaucophane. There appears also to be a chemical difference, as will be seen in the analyses quoted below, the iron being higher and the alumina lower than in any published analyses of glaucophane, except three from Rhodus, described by H. B. Foullon<sup>2</sup> as rhodusite, a variety of glaucophane. Foullon, however, did not give the optical orientation of the mineral, but stated that it lacked the violet pleochroism so characteristic of true glaucophane. It is probable that the mineral from Rhodus is either crossite or crocidolite. But since we have only one analysis of crossite, it is hardly proper to base conclusions on that.

Crossite has been identified in the Coast Ranges only in the albite-crossite gneiss from North Berkeley, in a quartz-glaucophane schist from Tiburon peninsula about a mile and a half north of the ferry, and in a metamorphosed quartz diorite from Oak Ridge, Santa Clara County, five miles east of Calaveras Valley. The last two occurrences were identified solely by the optical orientation, the analysis published by Palache being of the mineral from North Berkeley.

In some of the more ferruginous schists there is an asbestiform glaucophane-like mineral that is probably crocidolite, and a probable identification of this mineral has also been made in a dynamically metamorphosed albite syenite from Spanish Peak, Plumas County, where a brownish titaniferous hornblende (kataphorite) has frayed out at the ends in fine blue needles of crocidolite, with the characteristic pleochroism of that mineral.

<sup>1</sup>"On a Rock from the Vicinity of Berkeley Containing a New Soda-Amphibole," *Bull. Dept. Geol. Univ. Calif.*, Vol. I., pp. 181-192.

<sup>2</sup>Sitzb. Akad. Wien (1891), Bd. 100, pp. 172-174.

There can be no doubt that the blue amphibole that is so common in the metamorphic rocks of the Coast Ranges, from Oregon to San Diego, is mostly true glaucophane, for the writer has examined at least 300 slides from all over this great region, and has found the orientation to be that of the type from Syra, except in the cases mentioned above. It is likely, however, that a chemical study of this mineral from these different localities will disclose the presence of many varieties, some of which may eventually be designated by special names. It is associated with epidote, garnet, and lawsonite, and usually with mica, either muscovite, paragonite, biotite, or margarite. The rocks in which it is found are metamorphosed diorites, greenstones, pseudodiorites and pseudodiabases, eclogites and glaucophane schists.

It is probable that the variety gastaldite is present among the glaucophanes of California, for there are numerous occurrences of

TABLE OF ANALYSES OF GLAUCOPHANES.

	I. Glaucophane From Berkeley, Calif. Per Cent.	II. Glaucophane From San Pablo, Calif. Per Cent.	III. Glaucophane From Syra, Greece. Per Cent.	IV. Glaucophane From Syra, Greece. Per Cent.	V. Crosseite From Berkeley, Calif. Per Cent.	VI. Rhodusite From Rhodus, Greece. Per Cent.	VII. Gastaldite From St. Marcel, Italy. Per Cent.
SiO <sub>2</sub> .....	52.39	54.52	55.64	57.67	55.02	55.06	58.55
Al <sub>2</sub> O <sub>3</sub> .....	11.29	9.25	15.11	11.07	4.75	0.49	21.40
Fe <sub>2</sub> O <sub>3</sub> .....	3.74	4.44	3.08	3.20	10.91	15.48	
FeO .....	9.13	9.81	6.85	9.68	9.45	7.40	9.04
MgO .....	11.37	10.33	7.80	9.85	9.30	11.49	3.92
CaO .....	3.03	1.98	2.40	0.95	2.38	0.98	2.03
Na <sub>2</sub> O .....	6.14	7.56	9.34	6.80	7.62	6.38	4.77
K <sub>2</sub> O .....	trace	0.16		0.42	0.27	0.80	
MnO .....	trace	0.46	0.56	0.06	trace		
H <sub>2</sub> O .....	2.57	1.78		0.48		1.98	
TiO <sub>2</sub> .....	0.14	0.39					
Total.	99.80	100.68	100.78	100.18	99.70	100.06	99.71

I. Analyst, W. C. Blasdale, *Bull. Dept. Geol. Univ. Calif.*, Vol. II., 338.

II. Analyst, W. C. Blasdale, *Bull. Dept. Geol. Univ. Calif.*, Vol. II., 338.

III. Analyst, O. Luedecke, *Zeitschr. Deutsch. Geol. Gesell.*, Vol. 28, p. 249.

IV. Analyst, H. S. Washington, *Amer. Jour. Sci.*, 4th Ser., Vol. XI., p. 40.

V. Analyst, W. S. T. Smith, in C. Palache, *Bull. Dept. Geol. U. C.*,  
I., p. 188.

VI. Analyst, H. B. Foullon, *Sitzb. Akad. Wiss. Wien*, Vol. C, p. 174.

VII. Analyst, Cossa, *Accad. Linc. Rom.*, 1875, Vol. II., p. 33.

a pale blue mineral with the optical orientation and the pleochroism of glaucophane, but evidently poor in iron. In default of analyses of this variety it can not be assigned with certainty to gastaldite.

*Pargasite*.—In the basic eclogites of California the writer has found a black amphibole resembling pargasite from Pargas, but differing from that mineral in the orientation of its optical axes, and in its pleochroism. This mineral has been analyzed and its physical properties studied by Mr. W. O. Clark,<sup>1</sup> assistant in geology at Stanford University. It fuses readily to a black globule, and colors the flame yellow. It occurs abundantly in short, thick-set prisms with a cleavage angle of about  $124^\circ$ . It is monoclinic, with parallel extinction on planes in the zone of the symmetry axis, and on the clinopinacoid gives an extinction of  $c \wedge \epsilon$  about  $18^\circ$ . The axis of least elasticity is nearest to crystallographic  $c$ . The plane of the optical axes lies in the symmetry plane, and the  $a$  axis is the acute bisectrix, hence the double refraction is negative. The absorption is strong and the pleochroism decided,  $a$  = yellowish brown,  $b$  = deep olive green, and  $\epsilon$  = greenish blue. The absorption formula is  $b > \epsilon > a$ . The angle of the optical axes is very wide, being nearly  $90^\circ$ .

This mineral was first mentioned by Mr. R. S. Holway,<sup>2</sup> and by him doubtfully referred to pargasite. It is abundant in the black eclogites of Calaveras Valley, Santa Clara County, and has also been identified by the writer in a similar rock near Reed's Station on the Tiburon Peninsula. It is associated with glaucophane, carinthine, actinolite, red garnet, epidote, margarite, albite, and lawsonite, and is known in only those rocks that are unusually rich in iron. In these rocks the glaucophane is a later product than the pargasite, and appears only as a replacement rim around the latter. Pargasite is most nearly related to an amphibole made artificially in the wet way by Chrustschoff.<sup>3</sup> The artificial amphibole was black, and showed strong pleochroism from yellowish green to bluish green;  $c \wedge \epsilon$   $17^\circ 56'$ ,  $2 \vee$   $82^\circ$ , and sp. gr. 3.245.  $a$  and  $b$  = yellowish green, and  $\epsilon$  = bluish green. There is a re-

<sup>1</sup> Unpublished paper.

<sup>2</sup> *Journal of Geology*, Vol. XII. (1904), "Eclogites in California," p. 352.

<sup>3</sup> *Bull. Acad. Sci. St. Petersburg*, 23 Oct., 1890; and *Neues Jahrb.*, 1891, Vol. II., p. 86; cited by Hintze, "Handb. d. Min.," Vol. II., pp. 1232 and 1242.



markedly close agreement between pargasite from Pargas (Finland), that from Calaveras Valley, California, and the artificial amphibole made by Chrustschoff in chemical composition, orientation of the axes of elasticity and the pleochroism. Pargasite from Finland is optically positive, while that from California is negative, but that is a minor difference. Chemical analyses of pargasite from California, pargasite from Finland, and the artificial amphibole are given below on the table with the actinolite.

*Carinthine*.—This variety is rather common in the medium basic and acid rocks of the glaucophane series. It resembles pargasite, but is greenish rather than jet-black, and in thin sections the colors are not so dark. It occurs chiefly in long prisms, without terminal planes. The plane of the optical axes is the symmetry plane, the optical angle is wide and the character of the double refraction is negative. The extinction angle of  $\epsilon \wedge c$  is slightly smaller than in pargasite, varying from  $14^\circ$  to  $17^\circ$ . The pleochroism is strong,  $a$  = yellowish,  $b$  = light olive green,  $c$  = greenish blue. This mineral is common in the altered diorite near Searsville dam, Santa Clara County, in a similar rock three miles southwest of Redwood, in a quartz-lawsonite-glaucophane schist near the Schrader farm, two miles west of Redwood, in the eclogite of Oak Ridge, Santa Clara County, in the basic glaucophane schists at the Junction School House near Healdsburg, and in the glaucophane gneiss of Melitta, near Santa Rosa. No analyses were made of the mineral in these occurrences, but W. C. Blasdale<sup>1</sup> has described a similar variety in the glaucophane schists from near Berkeley. Blasdale's mineral has the same optical properties as those given above for carinthine,  $a$  = light green,  $b$  = yellow green, and  $c$  = bluish green. The analysis published by Blasdale and quoted below shows this mineral to be like the typical carinthine of the Alps, in its having lower magnesia and higher soda than common actinolite has. It is safe to say that the mineral described by Blasdale under the name of actinolite is the variety carinthine, which should be distinguished because of its association with glaucophane, both in California and in the Alps. It is quite likely that carinthine grades over into pargasite, but the two are rather distinct in their occur-

<sup>1</sup> *Bull. Dept. Geol. Univ. Calif.*, II., pp. 328-335.

rence and associations, the carinthine being more common in the rocks poorer in iron, and the pargasite in rocks where the iron is extremely abundant. Both appear to be older than the glaucophane which accompanies them, for that mineral is often found in replacement rims around the borders of the others, probably from later accession of sodium silicate due either to a further decomposition of plagioclase, or to the bringing in of soda by solutions.

*Actinolite*.—Common green actinolite of the variety smarag-

ANALYSES OF ACTINOLITE AND PARGASITE.

	I. Actinolite from Berkeley.	II. Actinolite from San Pablo.	III. Carinthine from Carinthia.	IV. Smaragdite from Lake Geneva.	V. Actinolite, Zillerthal, Alps.	VI. Pargasite from Finland.	VII. Pargasite from California.	VIII. Artificial Amphibole.
SiO <sub>2</sub> .....	55.21	55.56	49.33	54.30	53.10	41.26	42.68	42.35
Al <sub>2</sub> O <sub>3</sub> .....	3.45	2.05	12.72	5.15	4.10	11.92	9.96	8.11
Fe <sub>2</sub> O <sub>3</sub> .....			1.72			4.83	6.12	7.91
FeO .....	7.49	5.97	4.63	3.87	21.80	9.92	12.25	10.11
MgO .....	18.77	19.45	17.44	19.01	10.40	13.49	9.58	14.33
CaO .....	10.50	12.13	9.91	13.72	10.60	11.95	11.83	13.31
Na <sub>2</sub> O .....	2.45	1.94	2.25	2.80		1.44	3.30	2.18
K <sub>2</sub> O .....		0.30	0.63			2.70	0.89	1.87
H <sub>2</sub> O .....	1.75	2.58	0.29	0.30		0.52	3.28	0.91
TiO <sub>2</sub> .....							0.68	
Fi .....			0.21			1.70		
MnO .....							trace.	
Total .....	99.82	99.98	99.13	99.15	100.00	99.73	100.57	100.98

I. Actinolite from Berkeley, California; W. C. Blasdale, *Bull. Dept. Geol. Univ. Calif.*, Vol. II., No. 11, p. 333.

II. Actinolite from San Pablo, California; W. C. Blasdale, analyst, *loc. cit.*

III. Carinthine from Carinthia; Rammelsberg, analyst; cited in Hintze's *Handbuch der Mineralogie*, Vol. II., p. 1235.

IV. Smaragdite from Lake Geneva, Switzerland; Hunt, analyst; cited in Hintze, *op. cit.*, p. 1236.

V. Actinolite from Zillerthal, Alps; Beudant, analyst; cited in Hintze, *op. cit.*, p. 1235.

VI. Pargasite (black) from Finland; Rammelsberg analyst; cited in Hintze, *op. cit.*, p. 1239.

VII. Pargasite from Calaveras Valley, California; W. O. Clark, analyst (unpublished paper).

VIII. Artificial amphibole, made by Chrustschoff, cited by Hintze, *Handbuch d. Mineralogie*, Bd. II., p. 1242.

dite is very common in the glaucophane schists and eclogites, in long slender prisms and needles, with small extinction angles, and pleochroism from pale to bright grass green. This is often intergrown with glaucophane, and frequently shows replacement rims of that mineral. It sometimes results from the alteration of primary hornblende in the rocks, but more often from the uraliting of pyroxenes. Whether the smaragdite is soda-bearing has not been determined by analysis. Probably there is a complete intergradation between pargasite, carinthine and actinolite. The analyses quoted below show the composition of the bluish green actinolite from Berkeley and San Pablo, of the pargasite from Calaveras Valley, Santa Clara County, California, and for comparison the composition of carinthine from the Alps, of pargasite from Finland, of typical actinolite (smaragdite) from Lake Geneva, and of an artificial amphibole with the same chemical composition as pargasite.

*Diopside*.—The pale green variety of diopside without terminal planes, and with very high double refraction, known as omphacite, is rather common in the basic glaucophane-bearing rocks, especially in the eclogites. It is quite abundant in the eclogite from near San Martin, Santa Clara County, California, and also occurs in the glaucophane-lawsonite eclogite of Reed's Station near Tiburon, California. In appearance it resembles actinolite closely, but differs in its cleavage, and its high extinction angle in clinopinacoid sections.

The augite with fine orthopinacoid cleavage known as diallage, while essentially characteristic of igneous rocks, has been found in the eclogite of the Junction School-house near Healdsburg, as a secondary mineral associated with red garnet, glaucophane, margarite and titanite.

*Epidote*.—This mineral is very common in the basic metamorphics of the glaucophane series, but it is not the deeply colored mineral usually found in contact products. It is colorless, without pleochroism, and the interference colors in thin slides are not above the bottom of the second order. The crystals are elongated parallel to the symmetry axis, and consequently most sections give rectangular parallelograms with rather distinct cleavage parallel to the symmetry axis, and the optical figure across the plate. This variety

of epidote is poor in iron, and is very likely the mineral described by Becker<sup>1</sup> as zoisite, with which it is probably identical chemically.

*Zoisite*.—This is rare in the glaucophane rocks, being known to occur as an abundant constituent only in the basic schists associated with the eclogite of Hilton Gulch on Oak Ridge, Santa Clara County, California. Its form and appearance are exactly like the white epidote, with which it is associated, but its double refraction is very weak in all sections, the colors in thin slides not rising above blue-gray of the first order. A section of the white epidote cut normal to an optical axis can not be distinguished from zoisite in parallel light, but in convergent light the optical figure distinguishes the epidote. Below there is quoted from Becker an analysis of a mineral described by him as zoisite, although his description agrees exactly with the white epidote described above. The mineral analyzed was found in a glaucophane schist, of which the constituent minerals were glaucophane, zoisite (epidote?), quartz, muscovite (paragonite?), albite and titanite.

ANALYSIS OF ZOISITE (WHITE EPIDOTE?) FROM GLAUCOPHANE SCHIST.<sup>2</sup>

	PER CENT.
SiO <sub>2</sub> .....	39.80
Al <sub>2</sub> O <sub>3</sub> .....	22.72
Fe <sub>2</sub> O <sub>3</sub> .....	4.85
FeO .....	1.49
MgO .....	3.89
CaO .....	17.55
Na <sub>2</sub> O .....	4.09
K <sub>2</sub> O .....	0.12
TiO <sub>2</sub> .....	trace
MnO .....	0.26
H <sub>2</sub> O (above 100° C.) .....	5.25
Total .....	100.02

This pale epidote was described by F. L. Ransome<sup>2</sup> from an eclogite near Reed's Station on the Tiburon Peninsula, but it is also abundant in most of the eclogites and glaucophane schists of California.

A complete analysis of the glaucophane schist (No. 98, Sulphur

<sup>1</sup> Mon. XIII. U. S. G. S., p. 79.

<sup>2</sup> G. F. Becker, Mon. XIII., U. S. G. S., p. 79.

<sup>3</sup> Bull. Dept. Geol. Univ. Calif., Vol. I., No. 10, p. 310.

Bank), from which the supposed zoisite was separated, is given by Becker in the work cited. This analysis is quoted below in the table of analyses of the metamorphic rocks, and agrees very well with those of the ordinary basic glaucophane schists.

*Garnet.*—This is one of the most abundant minerals in the glaucophane rocks of California, but only in those rocks that have been entirely recrystallized. It is usually in the form of rhombic dodekahedrons, the only form observed, but in the pargasite eclogites of Calaveras Valley the garnet is in anhedral. It seems to be equally at home in the eclogites, glaucophane schists, and acid gneisses, so that the acidity and the basicity of the rocks have had no influence on its formation, which has been determined entirely by the intensity of the metamorphism. The crystals vary from extremely minute microscopic forms to those 15 mm. in diameter, the largest having been observed in the pargasite eclogite of Hilton Gulch on Oak Ridge, Calaveras Valley. It often occurs in large masses several inches long, but these are really aggregates of small crystals. The crystals in the eclogites are usually surrounded by a kelyphite ring, or reaction zone, of white mica, and chlorite is often formed in this same zone. Occasionally the garnet is entirely replaced by chlorite.

The garnet is, apparently, one of the last minerals to be formed, for, although it usually shows well-developed crystal faces, it contains inclusions of most of the other minerals. It is pale red, and appears to be of the same character in all of the glaucophane series, but as yet little chemical study has been made of the various occurrences. The only analysis of the garnet is that of the crystals in a diopside eclogite from Coyote Creek, about six miles north of San Martin, Santa Clara County, made by Mr. W. O. Clark, assistant in geology at Stanford University.

ANALYSIS OF GARNET FROM ECLOGITE ON COYOTE CREEK.

	PER CENT.
SiO <sub>2</sub> .....	38.69
Al <sub>2</sub> O <sub>3</sub> .....	19.10
FeO .....	26.81
MgO .....	5.07
CaO .....	10.64
Total .....	100.31

This corresponds to a mixed molecule, of approximately one-half alumina-iron garnet (almandine), one-sixth alumina-magnesia garnet (pyrope), and one-third alumina-lime garnet (grossular).

*Titanium Minerals.*—Sphene or titanite is abundant in small patches, more rarely in crystals, in most of the glaucophane rocks, but is especially characteristic of the more basic members of the series. The titanium appears to have been derived chiefly from the titaniferous hornblendes and pyroxenes of the original rocks. In the only partly recrystallized diabases and gabbros, where the augites have been uralited, or changed to actinolite or carinthine, the titanium has not remained in the ferro-magnesian mineral, but has separated out as leucoxene and titanite. In the partly recrystallized quartz diorite of Oak Ridge the original titaniferous hornblende has been changed on the borders to crossite, and the titanium has in this case, too, crystallized out as leucoxene and titanite. The same thing has been observed in a syenite of Spanish Peak in Plumas County, where the hornblende has been partly changed to crocidolite. In an orthoclase-glaucophane gneiss of Melitta sphene is abundant in sharply defined rhombs in thin sections, probably derived in the same way.

Rutile is rather common in minute crystals in most of the basic schists and eclogites, but in an eclogite from Coyote Creek near San Martin it is abundant in large crystals of 10 mm. in length. Its genesis is probably the same as that of sphene.

*Lawsonite.*—This is one of the most characteristic minerals in the glaucophane bearing rocks of California. It was first described by F. L. Ransome,<sup>1</sup> from the eclogite near Reed's Station on the Tiburon Peninsula. It has since been found to be abundant in schists, gneisses and eclogites from many parts of the Coast Ranges, and has also been found in similar rocks in Europe. Since it is such a constant companion of glaucophane, its occurrence and origin throw much light on the genesis of that mineral.

Lawsonite is orthorhombic in form, and of simple habit, the prism (110) and the basal pinacoid (001) being the commonest

<sup>1</sup> "On Lawsonite, a New Rock-forming Mineral, from the Tiburon Peninsula, Marin County, Cal.," *Bull. Dept. Geol. Univ. of California*, Vol. I., No. 10 (1895), pp. 301-312.

faces observed in the rocks, the prism faces meeting at an angle of  $67^{\circ} 16'$ ; consequently longitudinal sections usually give rectangular outlines, and basal sections rhombs. There are three cleavages, that parallel to the basal pinacoid, and that parallel to the brachypinacoid being rather distinct, while the cleavage parallel to the prism is faint. In longitudinal sections the pinacoidal and basal cleavages are at right angles to each other, while in basal sections the distinct brachypinacoidal cleavage bisects the obtuse angle ( $112^{\circ} 44'$ ) of the faint prismatic cleavage. The plane of the optical axis lies in the brachypinacoid (010) and the acute bisectrix is the axis of least elasticity, and is the normal of the basal plane. The character of the double refraction is therefore positive. Sections parallel to the vertical axis show high double refraction, and in thin slides show second order interference colors, while basal sections give weak double refraction and in thin slides show no higher color than yellow or orange of the first order. The orientation of the optical figure with reference to the cleavages and the axes of elasticity affords a ready means of identifying this mineral in microscopic sections. The relief is high and in thin sections the mineral is colorless, though in thicker sections and in macroscopic crystals the color is light blue. These characters make the determination of the mineral easy, even in minute crystals.

Two analyses of lawsonite are quoted below, both made of the mineral from the original locality. No analyses of this mineral

## ANALYSES OF LAWSONITE FROM THE TIBURON PENINSULA.

	I.	II.
SiO <sub>2</sub> .....	38.10	38.45
Al <sub>2</sub> O <sub>3</sub> .....	28.88	31.35
Fe <sub>2</sub> O <sub>3</sub> .....	0.85	0.86
FeO .....		0.10
MgO .....	0.23	0.17
CaO .....	18.26	17.52
Na <sub>2</sub> O .....	0.65	0.06
K <sub>2</sub> O .....		0.23
TiO <sub>2</sub> .....		0.38
H <sub>2</sub> O (above 100° C.) .....	11.47	11.21
MnO .....		trace
Total .....	98.39	100.33

I. F. L. Ransome, *Bull. Dept. Geol. Univ. of California*, Vol. I., 307.

II. Schaller and Hillebrand, *Amer. Jour. Sci.* (1904), p. 197.

have been made from other localities, but the physical properties are so striking that the identification is certain.

These analyses show that lawsonite is essentially a silicate of alumina and lime with two molecules of water,  $\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{H}_2\text{O}$ ; the iron, magnesia, alkalis and titanium may be neglected as probably coming from inclusions, and the mineral may be regarded as a metamorphic feldspathoid of the chemical nature of anorthite with the addition of water.

Lawsonite is known only as a product of metamorphism, and it is doubtful if a silicate with such a high percentage of water, over 11 per cent., could originate as a product of magmatic crystallization. It occurs only in rocks that have been more or less recrystallized; these are invariably rich in lime, and hence usually basic, though not necessarily so. It was described first from an eclogite rich in garnet, actinolite, glaucophane and margarite, and in nearly all the other rocks where it has been found glaucophane, or some other of the soda-bearing amphiboles, is a common associate, and albite occurs very commonly. On the other hand, garnet and epidote, which are abundant in most of the glaucophane-bearing rocks, are usually either lacking or scarce in the rocks with lawsonite.

The source of the lime for the lawsonite must have been the plagioclases which were abundant in most of the igneous rocks, the arkoses, and tuffs out of which the lawsonite rocks were made. The plagioclases were the first minerals to be disintegrated in the chemical readjustment that accompanied metamorphism. The albite molecule usually joined itself to pyroxenes or hornblende, forming glaucophane or some other member of the glaucophane group, and if there was an excess of sodium-aluminum silicate, it crystallized out as albite. If iron, alumina, and magnesia were in excess, the anorthite portion of the plagioclase molecule joined itself to them, forming garnet and epidote; but if there was an excess of lime, the anorthite molecule simply took up water and formed lawsonite. These reactions explain clearly why glaucophane is an almost invariable companion of lawsonite, why albite is a common associate, and why garnet and epidote do not usually occur in considerable quantity in lawsonite rocks.

Lawsonite occurs in glaucophane-bearing eclogites, in green-



stones, glaucophane schists, in lawsonite gneisses and schists, and in an altered quartz diorite, in which lawsonite and crossite are the only secondary minerals, the feldspars being only slightly altered in patches and the hornblende changed to crossite only around the borders.

*Feldspars.*—Orthoclase occurs rarely in the glaucophane rocks, and only in the acid schists and gneisses, for what little potash was in them has usually gone into the formation of muscovite.

Albite is very abundant in both acid and basic schists and gneisses, although it was almost never present in the original rocks. In the albite gneisses of Berkeley and Angel Island it makes up a large part of the rock, and in many others it occurs in veins and scattered through the mass. Its genesis is due to the decomposition of the plagioclase molecule, and to the crystallizing out of the excess of sodium aluminum silicate. It is not present in any cases where members of the glaucophane group have not been formed, which is sufficient proof that its presence indicates excess of soda.

Oligoclase has been observed in a quartz glaucophane gneiss near San Luis Obispo, but it was in small grains, and it was not possible to determine whether the grains were original fragments.

Labradorite, which is usually characteristic of igneous rocks, has been observed in considerable quantities in veins in a glaucophane eclogite from the Junction School-house near Healdsburg. It was determined by its extinction angles on the twinning planes, the orientation of its interference figure, and the character of its double refraction, all agreeing with labradorite. A qualitative test showed the presence of both lime and soda. Its occurrence in veins showed clearly that it is secondary.

*Zircon, etc.*—Zircon has been observed in minute crystals in the albite-crossite gneiss of Berkeley. Sillimanite occurs in the quartz-glaucophane schists of Catalina Island, and in similar rocks near San Luis Obispo. Cyanite, which is said to be a common companion of glaucophane in the glaucophane schists of Europe, was found in California only in a diopside-glaucophane eclogite on the San Francisco Peninsula. The rock was a small piece of float, and its original locality is unknown.

*Micas.*—No micas are known in the original rocks from which

the glaucophane rocks were made, and yet muscovite, paragonite and margarite are abundant, and biotite occurs rarely in the metamorphics. Muscovite is confined to the acid quartz glaucophane schists, probably made from original orthoclase in the arkose. Paragonite was probably made from the soda of part of the albite molecule when the plagioclase was disintegrated. In the lime rich rocks margarite is abundant, made from the excess of lime of the anorthite molecule when basic plagioclases were disintegrated. Biotite has probably the same origin as muscovite, with the addition of iron.

*Quartz.*—Recrystallized quartz occurs in all the rocks of the glaucophane series, in some forming the greater part of the mass. It was made partly from original quartz in the forms of grains and crystals, but in the diorites it was made from the excess of silica when more basic silicates, such as glaucophane, lawsonite, garnet and epidote, were formed.

*Chlorite.*—This is found in many of the rocks as a decomposition product, but in the actinolite schists it seems to be an original product of the recrystallization of basic rocks of the nature of pyroxenites. Actinolite is more acid than the original ferromagnesian minerals, and the residue would naturally be more basic.

*Talc.*—This occurs in large quantities in the lawsonite gneisses and schists. These rocks are made up largely of glaucophane and lawsonite, with crystal plates of talc scattered through them. The glaucophane is perfectly fresh, and there is no other magnesia-bearing mineral that might have given rise to the talc. The original rocks were probably made up of hornblende or pyroxene and plagioclase, and the disintegration of the plagioclase molecule furnished calcium silicate for the formation of lawsonite, while the albite molecule entered into combination with the hornblende or pyroxene to form glaucophane. The latter mineral requires more silica and less magnesia than the original hornblende or pyroxene, and there is left over an excess of silicate of magnesia, which crystallized out as talc. It is noteworthy that no garnets have been found in the rocks with talc, which shows that the metamorphism has not been so intense in this case.

*Other Minerals.*—Apatite, magnetite, and pyrite are present in small quantities in most of the glaucophane series, but only the

pyrite is of any importance in throwing light on the origin of the rocks. Its presence suggests that the metamorphism was aided by thermal solutions, which would naturally be alkaline, since only such solutions carry sulphur in any quantity.

#### TYPES OF GLAUCOPHANE-BEARING ROCKS OF CALIFORNIA.

The glaucophane-bearing rocks of California are varied in character, ranging from massive little altered igneous rocks to thin-bedded schists; but certain well defined groups may be distinguished under them. The groups defined below are independent of the genesis, based entirely on the petrographic character, for under most of them are found both rocks of sedimentary origin and rocks that were originally fused magmas.

##### I. *Eclogites*.

Eclogites were originally defined as massive rocks made up of garnet and omphacite, but since similar rocks often contain actinolite, glaucophane or other hornblendes as the chief ferro-magnesian mineral, the group has been extended to include these. All the eclogites known in California contain some glaucophane, although some other amphibole is often the predominant mineral. These rocks have been described by R. S. Holway,<sup>1</sup> and the principal minerals in them discussed. The typical variety, those composed of omphacite and garnet, is rare in California, having been described only from two localities. On Coyote Creek, six miles north of San Martin, Santa Clara County, is a massive rock composed of large dodekahedrons of red garnet, long prisms of omphacite, and a little glaucophane and white mica, probably paragonite. Some actinolite occurs in the rock, and abundant rutile in patches. This rock has been analyzed, and the results given on the next page are quoted from Mr. Holway's paper.

The sample analyzed did not contain any of the segregations of rutile. The estimated mineral constitution is approximately two parts red garnet, two of omphacite, and one of actinolite, glaucophane, and white mica together. The rock has the composition of a diabase, but the alumina, lime, and magnesia are lower than usual,

<sup>1</sup> "Eclogites in California," *Jour. Geol.*, Vol. XII., 1904, pp. 344-358.

and the iron and alkali higher. The published analyses that come nearest to that of this eclogite are those of the basalts of Kilauea, Hawaiian Islands, quoted by H. S. Washington,<sup>1</sup> in which the potash has a similar high percentage.

## ANALYSIS OF ECLOGITE FROM COYOTE CREEK.

	PER CENT.
SiO <sub>2</sub> .....	44.15
Al <sub>2</sub> O <sub>3</sub> .....	10.18
Fe <sub>2</sub> O <sub>3</sub> .....	11.92
FeO .....	13.04
MgO .....	6.18
CaO .....	4.51
Na <sub>2</sub> O .....	5.11
K <sub>2</sub> O .....	2.09
P <sub>2</sub> O <sub>5</sub> .....	0.20
TiO <sub>2</sub> .....	trace
H <sub>2</sub> O (above 100° C.) .....	0.95
Total .....	99.31

A very similar eclogite occurs in a large mass at Hadsell's farm, on the Arroyo Hondo, at the northern end of Calaveras Valley. No analysis was made of this rock, but it is composed of abundant dodekahedrons of red garnet often nearly a centimeter in diameter, long prisms of omphacite, a little titanite, lawsonite, colorless epidote, and white mica, probably paragonite. Glaucophane is scattered irregularly through the mass, in places making up the greater portion of it, so that the rock might be described as an eclogite in the restricted sense, or as a glaucophane eclogite, according to where the hand specimen was taken. A little albite was found in the slides, but always where the glaucophane was most abundant.

A very beautiful and characteristic eclogite occurs near Reed's Station on the Tiburon Peninsula, from which Ransome<sup>2</sup> first described the important rock-forming mineral lawsonite. The rock is massive but grades over into glaucophane schist. It is composed of red garnets from two to three mm. in diameter, with sharply defined dodekahedral faces, long prisms of smaragdite, some green omphacite, considerable glaucophane, and pale epidote, numerous large

<sup>1</sup> Prof. Papers No. 14, U. S. Geol. Survey, 1903, p. 325, Sylvester, analyst.

<sup>2</sup> "On Lawsonite, a New Rock-forming Mineral from the Tiburon Peninsula, Marin County, Cal.," *Bull. Dept. Geol. Univ. of California*, Vol. I., No. 10 (1895), pp. 301-312.

crystals of lawsonite, and plates of margarite. Sphene is scattered through the mass. In places the glaucophane is so abundant that the rock might appropriately be called a glaucophane eclogite.

Some of the California eclogites are remarkably like those of Syra in the Grecian Archipelago, from which glaucophane was first described. This resemblance is especially strong in the glaucophane eclogites of Camp Meeker in Sonoma County, and of the Junction School-house near Healdsburg. These are massive rocks made up of dodekahedral red garnets, and long prisms of glaucophane, with a little colorless epidote, and patches of titanite. A part of the Healdsburg eclogite is peculiar in having secondary diallage and secondary labradorite along with red garnet and margarite, and in showing replacements of both diallage and margarite by glaucophane. In both the Healdsburg and the Camp Meeker eclogites the garnets almost invariably show a kelyphite ring, or reaction zone, where mica has developed apparently at the expense of the garnet.

A new type of eclogite was described from Calaveras Valley by R. S. Holway.<sup>1</sup> This rock is composed of anhedral garnet and short thick prisms of an amphibole that is black in reflected light, and greenish blue in transmitted light. It fuses readily to a black magnetic globule, coloring the flame yellow, showing the presence of considerable sodium and iron. The pleochroism is intense, the *a* ray being pale greenish yellow; the *b* ray, deep olive green; and the *c* ray, greenish blue. The extinction angle of *C* on *c* is about 18°. This mineral has been determined as pargasite, and the rock called pargasite eclogite. Along with the pargasite some glaucophane is found in rims around the pargasite, and small quantities of white mica, either paragonite or margarite, and a little sphene and rutile. Albite is found as veins in the rock, but not disseminated through it. Colorless epidote is present in considerable abundance in some of the slides. This rock grades over into a pargasite schist or gneiss, without garnet, but considerable albite with small crystals of lawsonite scattered through it.

The handsomest eclogite found in California is that of Hilton Gulch on Oak Ridge, about five miles east of Calaveras Valley. This

<sup>1</sup> "Eclogites in California," *Jour. Geol.*, Vol. XII., 1904, p. 351.

is a massive rock made up of large dodekahedral red garnets more than a centimeter in diameter, thick prisms of black pargasite, thinner prisms of bluish carinthine, and plates of margarite, abundant blue prisms of glaucophane, a few small crystals of lawsonite, a little colorless epidote, and small crystals of rutile. This rock grades over into pargasite and margarite schists. Associated with it are ordinary glaucophane schists.

## II. *Pseudodiabases, Pseudodiorites, and Greenstones.*

Becker<sup>1</sup> introduced the terms pseudodiorite and pseudodiabase for certain basic metamorphic rocks, which he thought were metamorphosed sediments, in which the minerals were all products of recrystallization. These rocks contain plagioclase, hornblende, glaucophane, epidote, and zoisite, and, rarely, white mica. They occur in the form of dykes and sills, and often show a distinct porphyritic texture, even the ophitic structure of diabase being often visible in thin slides. Chemically, too, they are identical with normal diabases or metabasalts. But Becker<sup>2</sup> says that they were originally ordinary sandstones made up of the residue of decomposed granites, and that the magnesia was introduced into them, and all the minerals formed by hydrothermal action. Becker thought that this same process even made the serpentines of the Coast Ranges, where the magnesia was in great excess. Palache,<sup>3</sup> however has demonstrated that the serpentines of the Coast Ranges are made from genuine peridotites, and the writer has examined slides of serpentine from many parts of California showing abundant olivines and orthorhombic pyroxenes as original constituents. It is now recognized by all petrographers in California that these serpentines were originally genuine igneous rocks, and that in the process of serpentinization nothing has been added to them but water. And Ransome<sup>4</sup> has shown that the pseudodiabases and pseudodiorites of Becker are merely basic igneous rocks, metabasalts or "fourchites,"

<sup>1</sup> Mon. XIII., U. S. Geol. Survey, p. 94.

<sup>2</sup> Mon. XIII., U. S. Geol. Survey, p. 135.

<sup>3</sup> "The Lherzolite-serpentine and Associated Rocks of the Potrero, San Francisco," *Bull. Dept. Geol. Univ. of California*, Vol. I., pp. 161-179.

<sup>4</sup> "The Geology of Angel Island," *Bull. Dept. Geol. Univ. of California*, Vol. I., pp. 207 and 233.

in which some secondary mineralization has occurred. This fact too, is now so commonly recognized by petrographers familiar with the rocks of California that no further discussion is needed.

However, if the pseudodiabases do not show the remarkable phenomenon of the formation of a pseudo-igneous rock out of a sandstone, they do show something equally interesting,—the very beginning of the formation of a metamorphic out of an igneous rock. In some of the pseudodiabases and pseudodiorites all the original minerals and the original texture are still present, and the pyroxenes are only partly uralited to form hornblende. In others the readjustment has gone a little further, the feldspars have been partly changed to a saussuritic mass, and some secondary epidote and actinolite formed out of the pyroxene. In still others the feldspar has been entirely decomposed and a little soda taken from the albite molecule and added to the ferro-magnesian minerals, forming a little glaucophane or other soda-bearing amphiboles. In still others the original pyroxenes, even, have all been decomposed, and abundant epidote, diopside, glaucophane and white mica formed by the readjustment. There are all possible gradations from the little altered diabase to the entirely recrystallized glaucophane schists. The igneous rocks described as pseudodiorites, pseudodiabases, and fourchites are widely distributed in the Coast Ranges in the pre-Cretaceous, or Franciscan series, and have been the original materials out of which much of the basic glaucophane schists was made. Analyses of them are quoted below to show their perfect agreement with normal igneous rocks, and their unlikeness to any sediments except tuffs.

Widely distributed in the Coast Ranges occurs a group of rocks in which the metamorphism is more complete than in the pseudodiabases and pseudodiorites. The original feldspars are all decomposed, the pyroxenes either uralited or entirely recrystallized as other minerals, and secondary actinolite, epidote, zoisite, glaucophane and mica are formed. These rocks are massive, often occurring in the form of dykes, but they could hardly be called metadiabases, since some of them were certainly diorites, and others of them were probably made from the alteration of tuffs. They could hardly be called actinolite schists, since some of them contain little actinolite, and

they are usually massive, although they grade over into glaucophane schists and eclogites. Since they are usually of a greenish color, from the actinolite, diopside, epidote and chlorite in them, they have commonly been called "greenstones," and although this term has been misused in many vague senses, the writer prefers to call them by that name, restricting them to holocrystalline metamorphic massive rocks, regardless of whether they were made out of diabases, diorites or tuffs. In them the metamorphism has gone far enough to destroy entirely the original feldspars and pyroxenes; and diopside, epidote, zoisite, actinolite, carinthine, glaucophane, white mica, sphene and even occasionally lawsonite have been formed by the redistribution of the chemical constituents, but no garnet has been formed in them. They grade over on the one side to the little altered pseudodiabases and pseudodiorites, and on the other into schists and eclogites. The formation of the schists has taken place under what Van Hise<sup>1</sup> calls mass-mechanical conditions, and the eclogites were formed under mass-static conditions. When the metamorphism was less intense than in either case, the greenstones were made, and when the alteration was only slight, affecting only those minerals that were unstable even at comparatively low pressure in the presence of water, the pseudodiorites and pseudodiabases were formed.

A fine exposure of typical greenstone is seen on the Hellman ranch about two miles west of Redwood. It is massive, but grades over into glaucophane schist. The minerals that compose it are short prisms of diopside, rather slender actinolites and glaucophanes, abundant pale epidote, and patches of titanite. Pyrite is disseminated through the mass. Where the rock grades over into schist, glaucophane is more abundant, and rectangular sections of lawsonite occur as porphyritic constituents. In places this rock might even be called a lawsonite gneiss, on account of the massive banded structure, and the abundance of lawsonite. No analysis was made of the Hellman ranch greenstone, but a similar rock was described by Becker<sup>2</sup> as a pseudodiorite composed of actinolite, white mica, rutile, zircon and titanite.

<sup>1</sup> Mon. XLVII., U. S. Geol. Survey, p. 698.

<sup>2</sup> Mon. XIII., U. S. Geol. Survey, p. 101.



## ANALYSIS OF PSEUDODIORITE, "56 KNOXVILLE" (GREENSTONE).

	PER CENT.
SiO <sub>2</sub> .....	50.44
Al <sub>2</sub> O <sub>3</sub> .....	8.18
Fe <sub>2</sub> O <sub>3</sub> .....	1.06
FeO .....	6.28
MgO .....	17.63
CaO .....	11.55
Na <sub>2</sub> O .....	2.98
K <sub>2</sub> O .....	0.50
TiO <sub>2</sub> .....	
MnO .....	0.21
Cr <sub>2</sub> O <sub>3</sub> .....	0.48
H <sub>2</sub> O (below 100° C.) .....	0.07
H <sub>2</sub> O (above 100° C.) .....	0.92
Total .....	100.30

This rock is entirely recrystallized, but Melville's analysis of it shows that it is a normal diabase in composition.

Near the Hopkins reservoir, about three miles west of Redwood, is a massive greenstone, composed entirely of chlorite, pale epidote, and lawsonite, the latter occurring only in seams. It is associated with serpentine, and was probably originally a pyroxenite, for none of the minerals developed in it contain any quantity of soda. The original pyroxenes were probably rich in lime, and this has gone to the formation of lawsonite and epidote.

A quarter of a mile below the Searsville dam on San Francisquito Creek, Santa Clara County, is a very massive greenstone which seems to have been a dyke. It is somewhat banded, but not schistose. The groundmass is composed of feldspar which is mostly secondary albite, and through this are scattered long slender prisms of carinthine often with borders of glaucophane, rectangular sections of pale epidote and thin plates of white mica, probably paragonite. Chlorite occurs in irregular clusters, and quartz grains and patches of titanite are disseminated through the rock. The quartz may be original, but is more likely recrystallized either from original quartz, or from an excess of silica set free when the more basic epidote was formed. Very little glaucophane was formed, the albite portion of the feldspar molecule having crystallized out as albite, and the anorthite portion, instead of forming lawsonite, has taken up iron and formed epidote.

A rock similar to this in mineralogical constituents, but of a

gneissic structure, occurs a half mile southeast of the Hopkins reservoir, three miles southwest of Redwood. In this the feldspar and quartz are still more abundant, and the glaucophane less so. Both rocks appear to be recrystallized diorites, although either may be a metamorphosed dioritic arkose, or an acid adesitic tuff. They would both come under Becker's division of pseudodiorites.

Ransome<sup>1</sup> has described from Angel Island, under the name of "fourchite," a basic dyke rock which is identical with Becker's pseudodiabase. It is only slightly altered, having a little zoisite, and films and needles of glaucophane, the latter developed at the expense of the augite. Ransome found no feldspar in the slides studied by him, but H. W. Turner<sup>2</sup> found in other slides made from this mass abundant fresh plagioclase, from which he concluded that the so-called fourchite was merely a phase of diabase. The analysis quoted below from Ransome's paper shows that the rock agrees with pseudodiabase and with normal diabases or metabasalts in chemical composition.

ANALYSIS OF "FOURCHITE" FROM ANGEL ISLAND.

	PER CENT.
SiO <sub>2</sub> .....	46.98
Al <sub>2</sub> O <sub>3</sub> .....	17.07
Fe <sub>2</sub> O <sub>3</sub> .....	1.85
FeO .....	7.02
MgO .....	8.29
CaO .....	12.15
Na <sub>2</sub> O .....	2.54
K <sub>2</sub> O .....	0.53
P <sub>2</sub> O <sub>5</sub> .....	0.09
H <sub>2</sub> O (loss on ignition) .....	4.86
Total .....	101.38

### III. Diorite.

While there are many rocks in the metamorphic series of the Coast Ranges that were probably originally diorites, the writer has observed only one case where the identification was absolutely certain. On Oak Ridge, about five miles east of Calaveras Valley, was found a massive quartz diorite, in which incipient metamorphism

<sup>1</sup> *Bull. Dept. Geol. Univ. of California*, Vol. I., "Geology of Angel Island," pp. 200-207.

<sup>2</sup> "Notes on Some Igneous, Metamorphic and Sedimentary Rocks in the Coast Ranges of California," *Jour. Geol.*, Vol. VI. (1898), p. 483.

was observed. The original minerals were oligoclase, quartz, and a brown titaniferous hornblende, probably kataphorite. This rock has been slightly crushed, and the feldspars partly decomposed, setting free part of the albite and anorthite molecules. The albite did not crystallize out as such, but joined itself to the amphibole molecule, forming a glaucophane-like mineral, crossite, around the border of the undecomposed kataphorite. The crossite contains no titanium, and that constituent has taken up some of the lime to form titanite, and in other places has formed leucoxene. The anorthite molecule simply took up water and formed lawsonite, which occurs in and around the oligoclase in slender prisms. This rock is not a schist, nor even a gneiss, having probably been metamorphosed under mass-static conditions. Glaucophane schists were seen near the diorite, but they were apparently of more basic material. The agencies that made the schists also affected the diorite, but to a less extent.

On Spanish Peak, in Plumas County, at the northern end of the Sierra Nevada, the rocks have been much affected by dynamic action, quartzites having been changed to sericite schists, and conglomerates having been granulated until they have become fine-grained micaceous quartzites. At this place was observed a massive syenite that shows in thin sections the results of dynamic metamorphism. The rock was originally an albite, plagioclase hornblende mass, and most of the original minerals are intact. But the feldspars have become clouded through incipient decomposition, and the original brown hornblende has frayed out on the borders to a felt of asbestiform blue amphiboles that have the physical properties of crocidolite. Their pleochroism is intense, but lacks the violet shade that glaucophane and crossite always show. Their genesis is certainly the same as that of the crossite in the quartz diorite of Oak Ridge, from the addition of the albite molecule to the hornblende. This mineral was titaniferous, and the secondary crocidolite could not retain the titanium, which has then, as in the Oak Ridge diorite, separated out as titanite. This rock has not become a glaucophane schist, and none are known in the Sierra Nevada. Neither lawsonite nor epidote has been formed in the syenite, for the original feldspar was probably too acid to furnish the lime necessary for the formation of these minerals.

The chemical relations of the group of rocks and their transformation into glaucophane-bearing schists or gneisses are fully discussed below, in the section on "chemical readjustment in the metamorphism of the glaucophane-bearing rocks."

ANALYSIS OF QUARTZ DIORITE FROM OAK RIDGE, FIVE MILES EAST OF CALVERAS VALLEY, WITH SECONDARY CROSSITE AND LAWSONITE.

W. O. CLARK, ANALYST.

SiO <sub>2</sub> .....	61.55
Al <sub>2</sub> O <sub>3</sub> .....	17.48
Fe <sub>2</sub> O <sub>3</sub> .....	1.49
FeO .....	3.50
MgO .....	3.00
CaO .....	3.12
Na <sub>2</sub> O .....	8.47
K <sub>2</sub> O .....	0.07
H <sub>2</sub> O (— 110° C.) .....	0.12
H <sub>2</sub> O (+ 110° C.) .....	1.21
TiO <sub>2</sub> .....	0.28
Total .....	100.29

#### IV. *Glaucophane Schists.*

1. *Glaucophane garnet schists.*—The normal type of glaucophane schists, those with glaucophane, actinolite, pale epidote and garnet as the principal constituents, is widely distributed in the Coast Ranges. They are thin bedded, foliated and crumpled, showing intense crushing and shearing. All the minerals in them are the products of recrystallization, sometimes of igneous rocks, and sometimes of clay shales, possibly also of basic tuffs. The glaucophane is usually in the form of long blades and needles, the epidote in short thick-set prisms, and the garnet in dodekahedrons. Actinolite is an almost invariable companion of the glaucophane, and titanite is present in irregular patches, rarely in good crystals. This type of glaucophane schist is often associated with eclogite, and grades over into it, which shows that at least some of the holocrystalline basic metamorphics were made out of igneous rocks. Some of the garnet-glaucophane schists, however, are thought to have been made out of ferruginous clay shales, and Becker<sup>1</sup> says that a transition from the glaucophane schist to little altered shale was observed in

<sup>1</sup> Mon. XIII., U. S. Geol. Survey, p. 102.

the rocks of Mt. Diablo; Nutter and Barber<sup>1</sup> observed the same thing in the metamorphic rocks near Healdsburg.

The garnetiferous glaucophane schists resemble very closely those of Syra in the Grecian Archipelago, described by Lüdecke.<sup>2</sup> The minerals that compose it, and the rocks with which they are associated are the same in both. But one analysis of the garnet-glaucophane schist of California has been published, that given by H. W. Turner<sup>3</sup> of a schist from Pine Cañon, Mt. Diablo. This analysis is quoted below, along with another of a similar schist from Tupper Rock, near Brandon, Oregon, published by H. S. Washington.<sup>4</sup>

#### ANALYSES OF GARNET GLAUCOPHANE SCHISTS.

	I.	II.
SiO <sub>2</sub> .....	47.84	49.15
Al <sub>2</sub> O <sub>3</sub> .....	16.88	15.87
Fe <sub>2</sub> O <sub>3</sub> .....	4.99	4.10
FeO .....	5.56	7.58
MgO .....	7.89	7.53
CaO .....	11.15	9.06
Na <sub>2</sub> O .....	3.20	3.59
K <sub>2</sub> O .....	0.46	0.54
H <sub>2</sub> O (above 105° C.) .....	1.81	(above 110° C.) 1.07
H <sub>2</sub> O (below 105° C.) .....	0.17	(below 110° C.) 0.16
TiO <sub>2</sub> .....		1.19
MnO .....	0.56	trace
P <sub>2</sub> O <sub>5</sub> .....	0.14	
Total .....	100.65	99.84

I. Garnet-glaucophane schist, Pine Cañon, Mt. Diablo, California, Melville, analyst; H. W. Turner, *Bull. Geol. Soc. Amer.*, Vol. II., 1891, p. 418.

II. Garnet-glaucophane schist, Tupper Rock, near Brandon, Oregon, H. S. Washington, analyst; A Chemical Study of the Glaucophane Schists, *Amer. Jour. Sci.*, IV. Ser., Vol. XI., 1901, p. 53.

A comparison of these analyses with those of Ransome's fourchite and Becker's pseudodiabase, shows the agreement to be perfect, and it can not be doubted that they were all originally the same thing.

<sup>1</sup> "On Some Glaucophane and Associated Schists in the Coast Ranges of California," *Jour. Geol.*, Vol. X. (1902), p. 741.

<sup>2</sup> "Der Glaucophan und die Glaucophan führenden Gesteine der Insel Syra," *Zeit. Deutsch. Geol. Gesell.*, Bd. XXVIII. (1876).

<sup>3</sup> "The Geology of Mt. Diablo, etc.," *Bull. Geol. Soc. Amer.*, Vol. II., p. 418.

<sup>4</sup> "A Chemical Study of the Glaucophane Schists," *Amer. Jour. Sci.*, 4th Ser., Vol. XI. (1901), p. 53.

The localities where garnet-glaucophane schists have been found in California are too numerous to mention in detail, but the principal occurrences from which they have been studied are: Camp Meeker, Pine Flat, Junction School-house near Healdsburg, and Gurneville in Sonoma County; Tiburon Peninsula; San Pablo; North Berkeley; Mt. Diablo; Arroyo Hondo in Calaveras Valley; Oak Hill near San Jose; near San Luis Obispo; Santa Margarita ranch in San Diego County; Santa Catalina Island.

2. *Glaucophane-epidote Schists*.—This type of schist is even more common in the Coast Ranges than the garnet-glaucophane schist; it is almost invariably associated with the greenstones, and grades over into them. From the chemical nature and association of the rocks it would seem that the glaucophane-epidote schists are invariably the product of metamorphism of basic igneous rocks, or possibly from basic tuffs. All the minerals in them are the product of recrystallization, and if they were ever tuffaceous all evidence of the original fragmental nature is obliterated. Becker<sup>1</sup> described

#### ANALYSES OF EPIDOTE-GLAUCOPHANE SCHISTS.

	I.		II.		III.
SiO <sub>2</sub> .....	49.68		46.07		46.39
Al <sub>2</sub> O <sub>3</sub> .....	13.60		15.35		17.34
Fe <sub>2</sub> O <sub>3</sub> .....	1.86		3.61		6.32
FeO .....	8.61		9.87		4.62
MgO .....	6.27		7.83		4.93
CaO .....	10.97		4.37		13.07
Na <sub>2</sub> O .....	3.09		3.22		2.95
K <sub>2</sub> O .....	0.12		2.68		0.25
H <sub>2</sub> O (above 100° C.)..	3.84	(above 110° C.)	4.25	(above 110° C.)	1.48
H <sub>2</sub> O (100° C.).....	0.00	(below 110° C.)	0.16	(below 110° C.)	0.08
TiO <sub>2</sub> .....	1.31		1.63		0.85
MnO .....	0.04		trace		trace
P <sub>2</sub> O <sub>5</sub> .....	0.21				
CaO .....					2.24
Total .....	99.60		100.09		100.52

I. Epidote-glaucophane schist (98 Sulphur Bank, California); Melville, analyst; Becker, Mon. XIII., U. S. Geol. Survey, p. 104.

II. Epidote-glaucophane schist, Winston's Bridge, Orégon; H. S. Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI., p. 53.

III. Epidote-glaucophane schist, Kyperusa, Syra, Greece; H. S. Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI., p. 39.

<sup>1</sup> Mon. XIII., U. S. Geol. Survey, p. 104.

such a rock from Sulphur Bank, under the name of zoisite-glaucophane schist, but, as shown above, the so-called zoisite is probably a pale epidote. Besides this mineral Becker noted abundant glaucophane, and a little albite, white mica, quartz, and titanite. The analysis given of this rock by Becker is quoted below. A similar epidote-glaucophane schist has been described by Washington<sup>1</sup> from Winston's Bridge, near Roseburg, Oregon. The analysis given by Washington is quoted below, along with an analysis of an epidote-glaucophane schist from Syra in the Grecian Archipelago.

These rocks all agree in the abundance of epidote, the occasional presence of zoisite, and the absence of garnet. Chemically they agree exactly with the garnet-glaucophane schists, and with the pseudodiabases and fourchite, and they were all doubtless formed from metabasalt.

The chief occurrences in California of epidote-glaucophane schist that have been studied in detail are: Sulphur Bank in Colusa County; Junction School-house near Healdsburg; North Berkeley; Arroyo Hondo in Calaveras Valley, San Juan Mine at Oak Hill near San Jose.

3. *Glaucophane-lawsonite schists*.—Associated with the ordinary types of schists at a few places in California are found rocks composed almost exclusively of lawsonite and glaucophane. The glaucophane in fine needles forms a compact groundmass in which are imbedded rectangular prisms of lawsonite. Sphene is scattered through the mass in irregular patches. Neither garnets nor epidotes occur in any quantity in this type of schists. Talc is a common constituent of the lawsonite-glaucophane schists, and is apparently not a product of weathering, but was made at the same time with the other minerals. The original rock was either a basic igneous rock rich in lime and magnesia, or a basic tuff. When glaucophane was formed out of primary hornblende or pyroxene the excess of silicate of magnesia crystallized out as talc. No analyses have been made of the lawsonite-glaucophane schists, but estimates, based on a study of numerous thin sections, show them to have the constitution of diabases or diabase tuffs. They have been studied in detail at Guerneville; on the Hellman ranch three miles west of Redwood;

<sup>1</sup> *Amer. Jour. Sci.*, IV. Ser., Vol. XI., p. 53.

at the San Juan Mine, Oak Hill near San Jose; one mile south of the mouth of Coyote Canyon, Santa Clara County; and near Cayucas, in San Luis Obispo County. At all these places this rock is associated with epidote schists rather than with the garnetiferous type.

#### V. *Hornblende Schists.*

The hornblende schists do not make up independent rock-masses, but occur in subordinate quantities, associated with eclogites. They are of two principal types; those composed of the green prismatic actinolite, known as smaragdite, and chlorite, and those composed largely of pargasite. Both contain glaucophane in varying amounts, but the actinolite schists are characterized by the abundance of chlorite, while the pargasite schists contain abundant epidote and margarite. Carinthine occurs in both, especially where glaucophane is more abundant. As in all the basic schists of the glaucophane group, titanite is a common, and often an abundant constituent. The pargasite schists also often show secondary albite, but only in the rocks where little glaucophane is present. In both actinolite and pargasite schists glaucophane occurs as replacement rims around the more basic ferro-magnesian minerals. Both types grade over into eclogites and into basic mica schists.

The only analysis yet made of this group is that given by Becker<sup>1</sup> of a pseudodiorite. This analysis is quoted above, and shows the rock to have been originally a diabase. Some of the actinolite schists in the Coast Ranges are apparently still more basic, and were probably made out of the pyroxenites, or at any rate out of rocks very poor in feldspar. Slides of actinolite schist have been studied from Camp Meeker in Sonoma County; the Junction Schoolhouse near Healdsburg; Knoxville; Tiburon Peninsula near Reed's Station; near San Pablo; Arroyo Hondo at the north end of Calaveras Valley; Oak Hill near San Jose; a mile south of the mouth of Coyote Cañon, Santa Clara County; on Coyote Creek, six miles north of San Martin; near the Hopkins reservoir, about three miles southwest of Redwood; near Cayucas, in San Luis Obispo County. These schists also occur at many other places in the Coast Ranges where no detailed study of them has been made.

<sup>1</sup> Mon. XIII., U. S. Geol. Survey, p. 101.



Pargasite schists have been studied only from the Arroyo Hondo near the north end of Calaveras Valley; and from Hilton Gulch on Oak Ridge, about four miles east of Calaveras Valley. At the latter place carinthine is even more abundant in the rocks than pargasite. At both localities the pargasite schist grades over into pargasite eclogite.

## VI. *Mica Schists.*

There are two distinct types of mica schists in the glaucophane rocks of California, one associated with acid sediments, altered quartzites or cherts, and the other associated with basic schists, probably made out of diabases or diabase tuffs.

The acid schists are interbedded with layers rich in quartz, and probably represent clay-shale layers in original siliceous sediments. The mica in them is chiefly muscovite, although biotite sometimes occurs in considerable quantities. Garnet is almost invariably present in this type, and epidote almost never. No pyroxenes of any sort are found in them, and actinolite but rarely.

The basic mica schists are associated with eclogites and greenstones, and have no quartz. They are composed of paragonite or margarite, glaucophane, epidote, pargasite and carinthine. Where garnet is abundant in them they grade over into eclogite, and where garnet is lacking, and where mica is less abundant they grade over into greenstones. Neither the acid nor the basic mica schists make up independent rock-masses, but occur as bands in quartz glaucophane schists and in eclogites.

No chemical analyses have yet been made of either type, but slides have been studied of these rocks from many localities. The acid schists have been studied from Pine Flat, and the Junction School-house near Healdsburg in Sonoma County; from the Tiburon Peninsula, about one and a half miles north of Tiburon Ferry; from Belmont Hill, one mile southwest of Belmont; from Oak Hill near San Jose; from the Arroyo Hondo at the northern end of Calaveras Valley; from near Cayucas in San Luis Obispo County; and from a locality three miles west of Redwood, and a half mile southeast of the Hopkins reservoir. Biotite occurs in these as an abundant constituent only in the rock from near the Hopkins reservoir, and in that from the Tiburon Peninsula.

The basic mica schists have been studied from Camp Meeker, and from the Junction School-house in Sonoma County; from near Reed's Station on the Tiburon Peninsula; from Oak Hill near San Jose; from the Arroyo Hondo at the northern end of Calaveras Valley; and from Hilton Gulch on Oak Ridge, about five miles east of Calaveras Valley. At the two last localities the basic mica schists grade over into pargasite eclogites, and the micaceous mineral appears to be margarite.

## VII. *Glaucophane Gneiss.*

1. *Feldspathic Gneisses.*—The feldspathic gneisses of the glaucophane series are of two different types, the one with abundant orthoclase, and the other with albite as the dominant mineral. Neither type forms independent rock-masses, but both occur as bands in the ordinary glaucophane schists.

Orthoclase gneiss is known from but two places in the glaucophane rocks. The best example is that from a locality near Melitta in Sonoma County, California. This rock, which was found only in float, near a glaucophane schist outcrop, is massive and banded, with long prisms of glaucophane and actinolite in a groundmass of orthoclase and quartz. Small dodekahedrons of pink garnet and thin plates of muscovite are visible in the hand specimen. Thin slides show also abundant titanite in perfect rhombic sections. The glaucophane appears to have been formed after the actinolite, for it replaces the latter around the edges of the crystals. Part of the actinolite has a bluish color, suggesting that it may be carinthine. The glaucophane in this rock has the normal orientation of the axes of elasticity, but has an extremely narrow angle of the optical axes. Some of the bands are composed entirely of quartz with innumerable minute crystals of pink garnet and a few radial tufts of glaucophane. This rock was probably made out of an arkose, for no normal sediments could have the chemical nature necessary for its genesis, and it is hardly likely that an igneous rock would be interbanded with siliceous layers. It may, however, have been made from thin dykes of a granitic nature that were intrusive in the siliceous sediments.

Becker<sup>1</sup> has described from Sulphur Bank in Colusa County (No. 31, Sulphur Bank), a rock similar to that from Melitta. The

<sup>1</sup> Mon. XIII., U. S. Geol. Survey, p. 102.

PROC. AMER. PHIL. SOC., XLV. 183N, PRINTED JANUARY 9, 1907.

Sulphur Bank gneiss consists of quartz and orthoclase as a ground-mass, with large prisms of glaucophane, small plates of biotite and muscovite, small garnets, prisms of zoisite, and abundant titanite. Ilmenite and zircon were also observed in small quantities. Some plagioclase was also seen, probably albite, although it was not definitely determined.

An arkose slightly altered, which by further recrystallization would have made a feldspathic gneiss similar to those described above, has been described by Becker<sup>1</sup> from the Coast Ranges. This rock, No. 13, Sulphur Bank, Colusa County, is composed of quartz, orthoclase, plagioclase (albite?). No glaucophane has been developed in this rock, and Becker does not state what the ferro-magnesian mineral was, but it is presumably hornblende, since this would be present in either a granitic or a dioritic arkose. A chemical analysis of this rock by Melville is given by Becker along with his description, and this is quoted below.

ANALYSIS OF ARKOSE, No. 13, SULPHUR BANK.

SiO <sub>2</sub> .....	68.50
Al <sub>2</sub> O <sub>3</sub> .....	12.82
Fe <sub>2</sub> O <sub>3</sub> .....	1.29
FeO .....	3.37
MgO .....	2.27
CaO .....	1.82
Na <sub>2</sub> O .....	6.03
K <sub>2</sub> O .....	1.26
H <sub>2</sub> O (above 100° C.) .....	2.11
H <sub>2</sub> O (below 100° C.) .....	0.28
TiO <sub>2</sub> .....	0.60
P <sub>2</sub> O <sub>5</sub> .....	0.16
MnO .....	0.02
Total .....	100.47

Albite gneisses are described from but two places in the glaucophane-bearing series. That described by Ransome<sup>2</sup> from Angel Island consists chiefly of albite with some needles of glaucophane, plates of biotite, numerous very small crystals of garnet, and irregular patches of titanite. Quartz is entirely lacking in this rock, which is noteworthy, since the silica is so high.

<sup>1</sup>*Bull. Dept. Geol. Univ. of California*, Vol. I., p. 212.

<sup>2</sup>Mon. XIII., U. S. Geol. Survey, p. 92.

A similar rock has been described by Palache<sup>1</sup> from the Contra Costa Hills, three miles north of Berkeley. It is composed of a groundmass of albite, with numerous prisms of crossite, and some actinolite in parallel growth with the crossite. There are also a few grains of zircon and titanite.

Rosenbusch<sup>2</sup> has calculated the composition of the albite-crossite gneiss, and his estimate is quoted below.

	I.	II.
SiO <sub>2</sub> .....	65.2	67.53
Al <sub>2</sub> O <sub>3</sub> .....	15.8	18.57
Fe <sub>2</sub> O <sub>3</sub> .....	2.7	1.13
FeO .....	2.4	0.08
MgO .....	2.4	0.24
CaO .....	0.6	0.55
Na <sub>2</sub> O .....	10.8	11.50
K <sub>2</sub> O .....	0.1	0.10
H <sub>2</sub> O .....	(above 100° C.)	0.31
H <sub>2</sub> O .....	(below 100° C.)	0.15
P <sub>2</sub> O <sub>5</sub> .....		0.11
TiO <sub>2</sub> .....		0.07
Total .....	100.0	100.34

I. Estimated analysis of albite-crossite gneiss, Berkeley, Rosenbusch, *loc. cit.*, p. 712.

II. Analysis of soda syenite porphyry (No. 1521 S. N.), from the Sierra Nevada; Stokes, analyst; H. W. Turner, 17th An. Rept. U. S. Geol. Survey, pt. I., p. 727.

Turner says<sup>3</sup> that the soda syenite porphyry dykes of the Sierra Nevada are very like the albite-crossite gneiss in composition, and that when somewhat altered they often show a blue hornblende as a secondary mineral. He suggests that the feldspathic glaucophane gneisses of the Coast Ranges may be altered dykes. Turner does not state that the particular specimen of soda syenite porphyry selected for analysis contained the blue amphibole mentioned above, but this rock is probably identical with the albite syenite of Spanish Peak, Plumas County, California, which shows considerable quantities of a secondary blue amphibole, probably crocidolite.

2. *Quartz-glaucophane Gneiss*.—Siliceous glaucophane gneiss is very abundant in the Coast Ranges, often showing large masses. The rock is usually compact and massive, with gneissic banding,

<sup>1</sup> Bull. Dept. Geol. Univ. of California, Vol. I., p. 182.

<sup>2</sup> Sitzungsberichte d. K. Preuss. Akad. Wiss., 1898, p. 712.

<sup>3</sup> 17th An. Rept. U. S. Geol. Survey, Part I., p. 727.

but grades over into thin bedded acid mica schists. The constituent minerals are quartz, glaucophane, pink garnet, muscovite, actinolite and titanite, sometimes with a little feldspar. These rocks are undoubtedly siliceous sediments, either quartzite or chert, but everything in them is recrystallized, so that it is usually impossible to distinguish the product of the alteration of the quartzite from that of a chert.

Washington<sup>1</sup> has described from Four Mile Creek in Oregon a quartz glaucophane schist or gneiss, consisting of quartz, glaucophane, pink garnet, muscovite, and a little chlorite. The analysis given by Washington is quoted below.

A similar rock, but more massive and gneissic, occurs near Pine Flat, Sonoma County, on the Foss road from Calistoga to the Geysers, and near the house of J. Mueller. This locality is about two miles from the Geysers, and four miles from the Eureka mine. The rock is a massive banded gneiss, with abundant quartz, and muscovite, many long prisms of glaucophane, very small pink garnets, and a little actinolite. The glaucophane and actinolite are badly shattered, showing that at least a part of the crushing took place after they were formed.

A similar rock to that from near Pine Flat was studied by Nutter and Barber from the Junction School-house near Healdsburg.

On the Tiburon Peninsula, a mile and a half northeast of the Tiburon ferry is found a massive quartz gneiss. The rock contains abundant quartz, muscovite and biotite, numerous very small pink garnets, and a little actinolite, and small crystals and aggregates of titanite. There are numerous prisms that resemble glaucophane in appearance, but the pleochroism is more intense and the plane of the optical axes transverse, hence the mineral is the variety crossite. All the crystals in the rock are shattered, displaced and healed with secondary silica. Some of the clear glassy minerals may be albite, but none were found giving a biaxial figure.

Ransome<sup>2</sup> has described from Angel Island a quartz glaucophane gneiss very similar to that from the Tiburon Peninsula, and the two localities are not over two miles apart. But the Angel Island

<sup>1</sup>*Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 53.

<sup>2</sup>*Bull. Dept. Geol. Univ. of California*, Vol. I., p. 215.

gneiss has normal glaucophane instead of crossite. Ransome<sup>1</sup> has also published an analysis of a quartz glaucophane schist or gneiss from Angel Island, but it is impossible to tell from the context just which rock was analyzed. The analysis is quoted below.

A massive quartz glaucophane gneiss has been observed about a mile and a half southwest of Belmont. This rock is almost exactly like that described from near Pine Flat, except that no actinolite was found in the slides, and that the glaucophane is mostly in radial aggregates.

Similar massive quartz glaucophane gneisses have been studied from the Arroyo Hondo at the north end of Calaveras Valley; from Oak Hill near San Jose; and from near Cayucas in San Luis Obispo County. In the rock from the latter locality striated feldspar, probably albite, is rather common. Washington<sup>2</sup> has de-

#### ANALYSIS OF QUARTZ GLAUCOPHANE GNEISS.

	I.	II.	III.
SiO <sub>2</sub> .....	82.53	80.21	74.48
Al <sub>2</sub> O <sub>3</sub> .....	6.88	7.99	9.15
Fe <sub>2</sub> O <sub>3</sub> .....	0.59	3.35	1.41
FeO .....	4.11		4.12
MgO .....	1.86	1.54	3.04
CaO .....	0.68	1.10	2.84
Na <sub>2</sub> O .....	1.21	5.97	2.24
K <sub>2</sub> O .....	1.24	0.22	0.43
H <sub>2</sub> O (110° C.) .....	1.35	loss on ig. 0.74	(+ 110° C.) 2.06
H <sub>2</sub> O (110° C.) .....	0.07		(- 110° C.) 0.08
MnO .....	trace		
Total .....	100.52	101.12	99.85

I. Quartz glaucophane schist, Four Mile Creek, Oregon; Washington, analyst; *Amer. Jour. Sci.*, 4th Ser., Vol. XI., p. 53.

II. Quartz glaucophane schist, Angel Island, California; Ransome, analyst; *Bull. Dept. Geol. Univ. of California*, Vol. I., 231.

III. Quartz glaucophane schist, Little Harbor, Catalina Island, California; Washington, analyst; *Amer. Jour. Sci.*, 4th Ser., Vol. XI., p. 48.

scribed a quartz glaucophane gneiss from Little Harbor, on Catalina Island. The rock is fissile, composed of a groundmass of granular quartz, with numerous crystals and needles of glaucophane, and a few zircons and epidotes. No garnets are mentioned as occurring in this rock, and their absence is unusual in quartz glaucophane gneiss.

<sup>1</sup>*Op. cit.*, p. 231.

<sup>2</sup>*Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 48.

The slides from all the localities mentioned are so similar that the conclusion is unavoidable that all these quartz glaucophane gneisses were made from the same material, either a chert, or a very acid sandstone. The rock can hardly be called a quartzite, for while it is composed largely of quartz, there is no proof that it was made of rolled quartz grains.

3. *Lawsonite Gneiss*.—Lawsonite has long been known as an important mineral in the glaucophane schists of California, but has only recently been found to be a dominant mineral in some of these rocks. The rocks in which it is found as a dominant mineral are massive and gneissic, and although they contain no feldspars their structure is such that they must be called gneisses. They are known at present at only three localities. The first found is at Guerneville in Sonoma County, where bands of massive gneiss are apparently interbedded with lawsonite glaucophane schist. The rock is composed of crystals of glaucophane imbedded in a groundmass of lawsonite, the latter mineral showing few crystal outlines.

The most interesting lawsonite gneiss yet found occurs about three miles southwest of Redwood. It is massive and banded, showing a groundmass of lawsonite crystals, with a thick felt of compact prisms of glaucophane. Titanite is scattered through the rock in irregular patches, and the whole is seamed with quartz veins. Some layers show many small garnets. No trace of the original feldspars and hornblendes or pyroxenes is left, every mineral in it being secondary. The rock is composed of approximately one-fourth lawsonite, one-third glaucophane, one-third quartz, and one-twelfth garnet, titanite and mica. The total silica in the rock is 65.91 per cent., and originally there could have been very little free silica. The original minerals were probably oligoclase, hornblende and a little quartz, but in recrystallization more basic minerals were formed, setting free a large amount of silica which crystallized out in quartz veins.

An analysis of this rock was made by Mr. W. O. Clark, assistant in mineralogy at Stanford University, and this is quoted below.

The similarity of the analyses of the completely recrystallized lawsonite gneiss and of the slightly altered quartz diorite shows that the original material was the same in both cases.

	I.	II.
SiO <sub>2</sub> .....	65.91	61.55
Al <sub>2</sub> O <sub>3</sub> .....	11.62	17.28
Fe <sub>2</sub> O <sub>3</sub> .....	2.21	1.49
FeO .....	5.30	3.50
MgO .....	1.92	3.00
CaO .....	5.89	3.12
Na <sub>2</sub> O .....	1.95	8.47
K <sub>2</sub> O .....	0.04	0.07
H <sub>2</sub> O (100° C.) .....	0.28	0.12
H <sub>2</sub> O (red heat) .....	4.38	1.21
MnO .....	trace	trace
TiO <sub>2</sub> .....	0.17	0.28
Total .....	99.67	100.12

I. Lawsonite glaucophane gneiss, three miles west of Redwood; W. O. Clark, analyst.

II. Diorite with secondary crossite and lawsonite, Oak Ridge, five miles east of Calaveras Valley; W. O. Clark, analyst.

A lawsonite glaucophane gneiss very similar to that above described occurs a mile south of the mouth of Coyote Canyon, Santa Clara County, associated with lawsonite glaucophane schist. No chemical analysis was made, but the slides show the same minerals in about the same proportions. The original rock was probably a diorite, or at least a medium basic rock rich in lime.

## GENETIC CLASSIFICATION OF THE GLAUCOPHANE ROCKS OF CALIFORNIA.

### I. *Certainly Original Sediments.*

A. Quartz glaucophane schists, gneisses and altered cherts, at Pine Flat; Junction School-house near Healdsburg; Tiburon Peninsula; Angel Island; one mile west of Belmont; Arroyo Hondo at the northern end of Calaveras Valley; near Cayucas in San Luis Obispo County; Oak Hill near San Jose; and Catalina Island.

B. Altered tuffs and arkose; lawsonite and epidote glaucophane schists at the San Juan Mine, Oak Hill near San Jose, apparently derived from a tuff which occurs unaltered nearby; epidote glaucophane schists of North Berkeley; orthoclase glaucophane gneiss from Melitta near Santa Rosa, interbanded with quartzites.

C. Altered clay shales; basic glaucophane schists grading over



into unaltered shales, Junction School-house near Healdsburg; basic bands of glaucophane schist interbedded with quartz glaucophane schists and gneisses, Tiburon Peninsula; Angel Island; Pine Flat; one mile west of Belmont; Arroyo Hondo at the northern end of Calaveras Valley.

## II. *Certainly Original Igneous Rocks.*

A. *Basic Igneous Rocks.*—Pseudodiabase; pseudodiorite; some greenstones where they grade over into diabasic dykes; "fourchites," where they have been partly altered to glaucophane-bearing rocks; metabasalts of the Roseburg and Coos Bay Folios, Oregon. These rocks all occur as dykes or sills, possible sometimes as old surface flows. In some of the pseudodiorites and pseudodiabases the original minerals and the original structure are so well preserved that no one could doubt their igneous origin. And there is a complete gradation from these through rocks where the original structure is preserved, while the original minerals are recrystallized, into schists and greenstones where both original minerals and original structure are lost. This group grades over into basic epidote glaucophane schists and eclogites. The occasional association of these basic rocks with the acid schists can easily be explained by the hypothesis that the original clay shales and sandstones were invaded by dykes and sills of diabase, and that the whole complex, igneous as well as sedimentary rocks, was altered together.

B. *Diorite.*—The slightly altered quartz diorite of Oak Ridge five miles east of Calaveras Valley, shows the beginning of alteration in the formation of secondary crossite, lawsonite and titanite. The pseudodiorite on San Francisquito Creek, a quarter of a mile below the Searsville dam, Santa Clara County, shows a step further in metamorphism, in that the igneous nature of the rocks is still apparent, while nearly all the minerals in the rock are products of recrystallization. The lawsonite gneiss three miles southwest of Redwood shows the final product from such a rock, where the structure and the minerals are all secondary, and the chemical nature is unaltered.

A similar beginning of metamorphism has been observed in a syenite from Spanish Peak, Plumas County, where dynamic action

has caused a partial recrystallization, the plagioclases having given up some soda, which has joined the amphibole molecule, forming secondary needles of a blue glaucophane-like mineral, probably crocidolite. Soda syenite porphyry dykes are said by Mr. H. W. Turner<sup>1</sup> to show a secondary blue amphibole where some metamorphism has taken place, and he thinks that the albite glaucophane schists were probably made out of such material.

### III. *Doubtful Original Sediments.*

Under this head must be classed many of the basic glaucophane rocks that are interbanded with more acid rocks of sedimentary origin. They were probably originally tuffs, but in many cases they may have been flows or sills. These appear as schists and greenstones, but their field relations often give no indication as to their origin, and they are so thoroughly recrystallized that their original fragmental nature is lost.

### IV. *Doubtful Original Igneous Rocks.*

In the Coast Ranges there are many masses of holocrystalline rocks that resemble igneous rocks in their structural relations, but are made up entirely of secondary minerals. Where they do not grade over into undoubted igneous rocks their origin must remain in doubt, for a chemical analysis can not show whether they were originally fused magmas or fragmental tuffs. These rocks are eclogites, greenstones and basic schists, grading over into each other, and with the chemical constitution of gabbros or diabases, more rarely of diorites. Some of the more basic eclogites may even have been made out of pyroxenite. The eclogites are massive or gneissic, composed of garnet, omphacite, some amphibole, and epidote. The greenstones are essentially omphacite actinolite epidote rocks, and the schists associated with them are usually epidote glaucophane schists with either paragonite or margarite. No eclogites have been found that grade over into dioritic rocks, or have the chemical composition of that group, but the lawsonite schists and gneisses with their high percentage of lime and comparatively low iron and magnesia suggest a derivation from diorites.

<sup>1</sup> 17th An. Rept. U. S. Geol. Survey, Part I., p. 727.

The albite schists and gneisses, described above, at least have the composition of soda syenites, and must have been made from such rocks, or from tuffs or arkose derived from them.

#### CHEMICAL READJUSTMENT IN THE METAMORPHISM OF THE GLAUCOPHANE-BEARING ROCKS.

*Igneous Rocks.*—The original igneous rocks and the metamorphic glaucophane-bearing rocks made out of them have the same chemical constitution, for there has been little addition. But the two groups invariably differ mineralogically, for even when the same mineral species occurs in the two groups, it is represented by different varieties, one a characteristic product of crystallization out of a fused magma, and the other the product of solutions under pressure. When the metamorphism has not been intense, some of the original minerals have persisted, but in most cases every mineral in the glaucophane rocks is a product of recrystallization.

The feldspars, hornblendes and pyroxenes have been the chief factors in the readjustment. The orthorhombic pyroxenes have invariably decomposed, none being found in any of the metamorphic rocks of the glaucophane series. The monoclinic pyroxenes have fared little better, having usually been uralited to form some variety of amphibole, with the probable addition of soda in most cases. More rarely they have formed diopside, and in one instance secondary diallage has been observed, in the altered glaucophane-bearing gabbro of the Junction School-house near Healdsburg.

The original hornblendes and pyroxenes of the igneous rocks of the Coast Ranges of California have often been titaniferous, but the secondary minerals resulting from them by metamorphism generally contain no titanium. Hence, when glaucophane, epidote, zoisite, or garnet was formed there was a certain amount of titanic oxide set free, which either crystallized out as rutile, or took up lime and formed sphene or titanite. Fringes of titanium minerals are common around the original titaniferous hornblendes or pyroxenes where the readjustment has begun.

In the feldspars the readjustment has been still more fundamental, for the material of which they were composed has been distributed in the formation of entirely different minerals. The original feld-

spars were mostly orthoclase, andesine, oligoclase, and labradorite. Of these andesine is unknown in the glaucophane rocks of California, labradorite as a secondary mineral in only one case,—in veins in the altered glaucophane-bearing gabbro of the Junction School-house near Healdsburg. Orthoclase is very rare, although it occurs in considerable abundance in some gneissic rocks. On the other hand, albite is very rare as an original constituent of the igneous rocks of the Coast Ranges, but is a very common companion of glaucophane in the metamorphics. The explanation of this is simple. The lime-soda feldspars are formed readily in fusions, but not readily in the wet way. On the other hand, it has been demonstrated by experiment that the alkali-feldspars, orthoclase and albite, are formed readily in superheated solutions under pressure, and not readily in magmatic fusion. Since the plagioclase molecule is unstable in the presence of water in hydrothermal metamorphism, oligoclase, andesine and labradorite are the first minerals to be broken up. The anorthite portion of the lime-soda feldspar is set free to form lime-rich minerals, either by taking up water to form lawsonite, or by taking up iron and alumina to form garnet and epidote. The albite portion of the molecule either joins with the ferro-magnesian minerals to form glaucophane or other soda-bearing hornblendes, or, if it is present in excess, crystallizes out as albite. This accounts for the fact that albite is the commonest feldspar in metamorphic rocks, not only in California, but all over the world, and that lawsonite is a common companion of glaucophane, in Europe as well as in California.

In the Coast Ranges are found considerable quantities of very basic actinolite schists with a small amount of glaucophane. These rocks appear to have been made out of pyroxenites, in which soda was very scarce, for olivine, augite and orthorhombic pyroxenes contain no soda. In addition to actinolite and glaucophane, the rock contains large quantities of chlorite not made at the expense of the actinolite, which is perfectly fresh. A mixture of about two-thirds actinolite and one-third chlorite would give the composition of the original pyroxenes; for when the basic ferro-magnesian mineral is broken down to form actinolite there is left a more basic portion rich in magnesia to form chlorite by the addition of water. Since

the original rock contained soda only in extremely small quantities the blue hornblendes are developed only rarely in the secondary rocks resulting from them. When soda was more abundant some of it went to the formation of paragonite, and when there was an excess of lime in the pyroxenes it went largely into margarite. Both of these minerals are quite common in the basic schists and eclogites.

In the medium-basic rocks, gabbros and diorites, which form the bulk of the older igneous rocks of the Coast Ranges the products of metamorphism are much more varied. The first step is simply the formation of paramorphs of hornblende after pyroxene, uralitization, without any fundamental chemical readjustment. But when the lime-soda feldspars were partly broken down some of the soda went into the amphibole molecule and actinolite was formed. Since this mineral contains no titanium, while the original hornblende and pyroxene were often titaniferous, titanite was set free, and either crystallized out as rutile, or combined with lime to form titanite. These are both very abundant in the basic metamorphics of this group.

The silica, lime, and alumina set free from the feldspars often took up iron from the ferro-magnesian minerals to form more basic silicate, usually epidote, and sometimes zoisite when the iron was deficient. When the feldspars were more broken down and more soda set free, or more soda added from outside sources, bluish pargasite was formed, accompanied by large quantities of white epidote. In other cases, but usually in the more acid diorites, the bluish green soda-bearing hornblende, carinthine, has been formed in considerable quantities. In the pargasite-bearing rocks there was more of the albite molecule set free than was needed for the formation of pargasite, and this has crystallized out in veins of very pure albite.

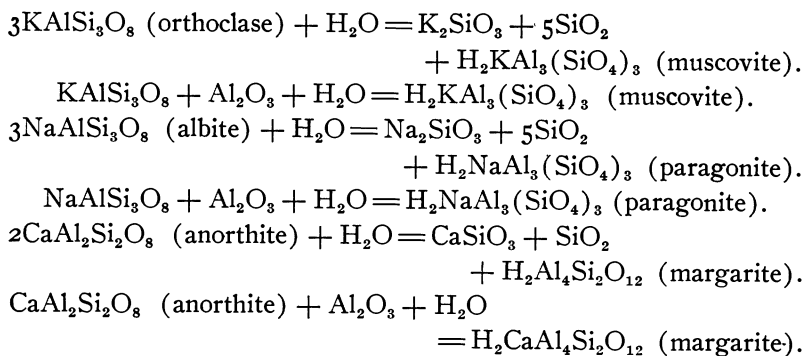
When still more soda was released from the feldspars glaucophane was formed, while the excess of lime went into garnet, more rarely into lawsonite, accompanied as before by white epidote. In some of the basic eclogites diopside is common, and in this case little epidote was formed, the excess of lime having gone into garnet.

When the rocks are low in silica and rich in lime, lawsonite has often been formed in great abundance by the plagioclase giving up

its soda to form glaucophane, and setting free the anorthite molecule,  $\text{CaAl}_2\text{Si}_2\text{O}_8$  which by taking up water becomes lawsonite,  $\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{H}_2\text{O}$ . When this has taken place little epidote was formed, and usually no garnets, although in the rock from which lawsonite was first described both garnet and epidote are abundant.

As evidence that the metamorphism that produced the uralite and pargasite rocks was not so fundamental as that which formed the glaucophane, it may be stated that the pargasite rocks are more massive, and not true schists, and that in these rocks the glaucophane appears as replacements or rims around the pargasite. Most of the schistosity has been produced after the glaucophane was formed, for even that mineral is usually bent and fractured, the cracks being healed with secondary silica, forming quartz veins which occur as innumerable small seams through these rocks.

No original micas of any sort are found in the gabbros and medium basic diorites of the Coast Ranges, and yet the eclogites, glaucophane schists and gneisses are full of white mica, chiefly the sodium-bearing paragonite and the lime-bearing margarite. These are formed at the expense of the plagioclases, either by their giving up silica and alkali-silicate, or by their taking up alumina from aluminous silicates. The reactions given below show how the micas may have been formed.

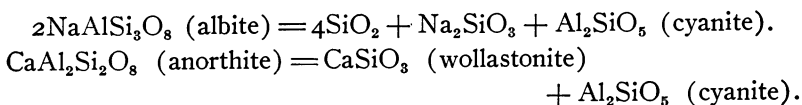


Neither albite nor anorthite occurs in the original igneous rocks from which these metamorphics were made, but the albite and the anorthite molecule are both abundant in the plagioclases which made up a large portion of those rocks. All three of these micas

are known as incrustations or reaction zones on corundum, having been formed by the adjacent feldspars taking up alumina directly from the corundum. And muscovite, paragonite and margarite are all common as kelyphite rings or reaction zones around garnets, accompanied by chlorite. In this case the feldspar molecule has robbed the garnet of part of its alumina, forming mica, and the residue, richer in magnesia, has taken up water to form chlorite. This phenomenon is especially common in the eclogites.

The potash-rich igneous rocks have given rise to metamorphics with muscovite, the soda-rich original rocks have formed metamorphics with paragonite, and the lime-rich igneous rocks have gone over into schists or eclogites with margarite. Naturally the more acid rocks usually have more muscovite, and the more basic ones more paragonite or margarite.

Cyanite has been described as abundant in the European glaucophane schists and eclogites, and its possible mode of formation is shown by the reactions:



But wollastonite is not known to occur in the glaucophane rocks anywhere, and cyanite has been found in these rocks in California only in one eclogite, the wollastonite and cyanite molecules having joined themselves to others, forming more complex silicates. Sillimanite, which has the same composition as cyanite, is not uncommon in the siliceous rocks of the glaucophane series.

The medium basic plagioclases are common in the diabases, gabbros and basic diorites of the Coast Ranges, and from these have come the bulk of the glaucophane-bearing schists, greenstones and eclogites. When the readjustment is only partial, we have massive rocks composed of partly decomposed feldspar (saussurite), uralite, and carinthine, with a little sphene and epidote or zoisite. These rocks are the pseudodiabases and pseudodiorites of Becker. When the disintegration of the plagioclase molecule is more complete, part of the anorthite molecule takes up water and crystallizes out as lawsonite, while a portion of the albite molecule crystallizes out as

albite in veins or patches, and the rest is taken up by the ferromagnesian minerals to form glaucophane, or when soda is deficient, carinthine or pargasite. In the aluminous calcium augite there was more lime than was needed for the formation of glaucophane, and epidote was produced in considerable quantities, but when the original minerals were olivine or orthorhombic pyroxene there was no excess of lime. Thus in the metamorphics made from rocks of the nature of peridotites epidote and garnet are rare, while they are plentiful in those made from diabases and diorites.

When the amount of iron was higher than was needed for the glaucophane, and the lime too low for lawsonite, the iron-alumina garnet was formed, as in the black pargasite, and green actinolite and omphacite eclogites. And when the iron, alumina, lime and soda were all abundant, then glaucophane, red garnet, lawsonite and epidote were all formed together, as in the Tiburon eclogite. All this, of course, refers only to the predominating minerals, since in any of the metamorphic rocks of the basic series small quantities of either glaucophane, lawsonite, garnet, or epidote may occur.

Near the Searsville dam in Santa Clara County is a diorite in which the metamorphism is fundamental, every mineral in the rock being secondary, and yet the rock is still recognizable as a diorite. It is composed of carinthine, epidote, white mica, probably paragonite, albite, and abundant quartz, with titanite and pyrite scattered through the mass. A little glaucophane appears as replacements of the carinthine. The original plagioclases have been almost entirely decomposed, and the hornblende or pyroxene remade into carinthine by losing titanium and taking up part of the albite molecule from the plagioclase. No lawsonite nor garnet was made out of the anorthite molecule, but abundant epidote instead. This formation of more basic minerals has set silica free, and this has crystallized out as quartz in veins and patches all through the rock. As there was too much albite in the original feldspar for the needs of the carinthine and glaucophane, albite has crystallized out in veins, and the residue of the molecule took up alumina and formed paragonite. The crystals of pyrite in the mass tell of the nature of the solutions that aided in the readjustment.

On Oak Ridge in Santa Clara County, about five miles east of



Calaveras Valley, is a massive quartz diorite, in which the metamorphism has only just begun, and all the original minerals may be recognized. The rock is composed of original quartz, oligoclase, and brown hornblende (probably kataphorite), with a little secondary lawsonite and glaucophane (crossite). The readjustment consists in the partial breaking up of some of the oligoclase, and the addition of some of the albite molecule to the borders of the brown hornblende to form a fringe of glaucophane (crossite). Since the glaucophane contains no titanium, this constituent crystallized out around the borders of the parental mineral as titanite and leucoxene. Most of the oligoclases are still perfectly fresh, and those partially decomposed still show their outlines and twinning bands, giving evidence of decomposition in cloudiness due to kaolinization. The little lime they contained went to formation of lawsonite, which is present in minute crystals, with the characteristic optical properties of that mineral.

The original oligoclase, from its extinction angles on the twinning bands, has the composition of  $Ab_3An_1$ , with 63 per cent. silica. The small quantity of the anorthite molecule set free simply took up water and formed lawsonite,  $CaAl_2Si_2O_8 + 2H_2O$ . The albite molecule was disintegrated, giving sodium silicate to the hornblende to form glaucophane, and setting free kaolin and silica;  $2NaAlSi_3O_8 + 2H_2O = Na_2SiO_3 + 3SiO_2 + H_2Al_2Si_2O_8 + H_2O$  (kaolin). In this none of the sodium silicate and little of the silica was left free, but went into combination with the hornblende on the borders to raise the percentage of silica and soda to that necessary to form glaucophane. The rock is composed of approximately four parts oligoclase, two of hornblende and one of quartz. This has nearly the same composition as that of the albite-crossite gneiss of Berkeley, and the albite-glaucophane gneiss of Angel Island. The analysis of the quartz diorite with secondary crossite and lawsonite is given below.

About three miles west of Redwood is a massive gneissic rock composed of approximately one-fourth lawsonite, one-third glaucophane, one-third silica (quartz), and the remaining one-twelfth of garnet, sphene and white mica. Every mineral enumerated above is clearly secondary, and yet the analysis given below is that of a

quartz diorite. Even the quartz, which makes up about one-third of the rock, is secondary, for there could not have been any such quantity of free quartz in the original rock with only 66 per cent. of silica. The original minerals were probably oligoclase, hornblende, and quartz, and the addition of 4 per cent. water has lowered the silica from 68 per cent. to 65.9 per cent. The original hornblende was probably titaniferous, for numerous small aggregates of titanite are visible in the slides. The original rock was probably a quartz diorite similar to that of Oak Ridge described above, but with the readjustment complete. A chemical analysis of this rock by Mr. W. O. Clark, assistant in geology at Stanford University, gave the following results:

	LAWSONITE GNEISS.	DIORITE WITH CROSSITE.
	I.	II.
SiO <sub>2</sub> .....	65.91	61.55
Al <sub>2</sub> O <sub>3</sub> .....	11.62	17.28
Fe <sub>2</sub> O <sub>3</sub> .....	2.21	1.49
FeO .....	5.30	3.50
MgO .....	1.92	3.00
CaO .....	5.89	3.12
Na <sub>2</sub> O .....	1.95	8.47
K <sub>2</sub> O .....	0.04	0.07
H <sub>2</sub> O (100° C.) .....	0.28	0.12
H <sub>2</sub> O (above 110° C.) .....	4.38	1.21
MnO .....	trace	trace
TiO <sub>2</sub> .....	0.17	0.28
Total .....	99.67	100.12

I. Lawsonite gneiss, three miles west of Redwood, W. O. Clark, analyst.

II. Quartz diorite with some secondary crossite and lawsonite, Oak Ridge, five miles east of Calaveras Valley, W. O. Clark, analyst.

A comparison of these two analyses shows the lawsonite gneiss to have been more like an ordinary quartz diorite in composition; while the diorite with secondary crossite is somewhat allied chemically to the soda syenite porphyries.

About one mile south of the mouth of Coyote Cañon, Santa Clara County, is a mass composed of glaucophane schist, lawsonite-garnet-glaucophane gneiss, and lawsonite-glaucophane schist. In the latter phase both lawsonite and glaucophane are perfectly fresh, but there is a large amount of talc formed, which was clearly not made at the

expense of any mineral now visible in the rock. The original rock must have been richer in magnesia than the needs of the glaucophane demanded, and as no garnets or epidotes were formed the excess of magnesium silicate crystallized out as talc, in this case a primary constituent of the rock, and not a weathering product. This could only happen where the metamorphism was not very intense, and the absence of garnets would show that this was the case. No analyses have been made of this rock, but an estimate made from a study of numerous slides shows that the original material must have been a basic igneous rock or a basic tuff.

*Sedimentary Rocks.*—The altered sediments containing glaucophane are: (1) Basic tuffs, probably of the character of diabase; (2) arkose, of the character of granites or diorites; (3) sandstones, with varying proportions of impure clay; (4) clay shales, with varying proportions of sand and other impurities.

The basic tuffs consist largely of augitic and feldspathic fragments, and these recrystallize very readily. From this material have been formed schists composed largely of glaucophane and epidote, with accessory titanite, garnet and zoisite. The reactions here are the same as in the recrystallization of diabases and gabbros, the high percentage of iron usually necessitating the formation of abundant epidote.

While feldspars are usually present in small quantities in the altered acid sediments, they are known in large quantities in but few places in California. The arkoses usually have the composition of granites or acid diorites, and the recrystallization products are of the same chemical nature. In the gneiss from Melitta near Santa Rosa the original rock was an arkose composed of fragmental hornblende, orthoclase, acid plagioclase, and quartz. The orthoclase has recrystallized as such, the original hornblende has formed actinolite, and some of it has taken up soda, forming mixed crystals of carinthine and glaucophane. Some of the original ferro-magnesian mineral was probably titaniferous, for titanite is abundant in the rock. The excess of iron, alumina and magnesia from the partial decomposition of the hornblende and plagioclase formed abundant red garnets. It is noteworthy that neither epidote nor lawsonite nor any pyroxene was formed.

The albite-crossite gneiss of North Berkeley may have been formed from a syenitic arkose, as also the albite glaucophane gneiss of Angel Island. The lawsonite gneiss from near Redwood may have been a dioritic arkose, for its chemical composition is almost exactly that of a quartz diorite. The albite gneiss and the lawsonite gneiss both resemble somewhat in composition the altered arkose described by Becker,<sup>1</sup> which is evidently made up of fragmental material from a diorite or a granodiorite.

Sandstones usually contain varying proportions of clay, partly decomposed feldspars, and ferro-magnesian minerals. The feldspars were in part orthoclase, for we sometimes find this mineral in siliceous glaucophane schists. But more often we find evidence of the former presence of a potash feldspar in the secondary muscovite, which is almost never absent in this group. The silica has simply recrystallized as quartz, whether it came from original sand grains, or from the organic silica of the chert. Plagioclases are rarely present in the recrystallized product, but evidence of their former presence is seen in the soda that went into the glaucophane, and the lime and alumina that went into the garnets. Titanite is always present in the recrystallized siliceous rocks, but its origin is somewhat doubtful. The titanium probably came from titaniferous hornblendes, which on recrystallization took up soda to form carinthine or glaucophane and set free titanium. No pyroxenes of any kind are found in the recrystallized acid rocks. No epidote has been found in the siliceous rocks of the Coast Ranges, the lime of the plagioclase having invariably gone into the formation of garnet.

The reactions of the clay shales are essentially the same as those of the sandstones, except that there is usually more impurity in the shales, and consequently a greater variety of minerals. Glaucophane, garnet and white mica are the chief products, with subordinate quartz, from sand grains. No cyanite nor andalusite has been observed in any of the aluminous shales, though they would be expected, from the preponderance of silicate of alumina, and sillimanite occurs very rarely.

<sup>1</sup> Mon. XIII., U. S. Geol. Survey, p. 92.

TABLE OF ANALYSES.

	I. Quartz Glaucophane Schist.	II. Quartz Glaucophane Schist.	III. Quartz Glaucophane Schist.	IV. Altered Arkose.	V. Lawsonite Gneiss.
SiO <sub>2</sub> .....	82.53	80.21	74.48	68.50	65.91
Al <sub>2</sub> O <sub>3</sub> .....	6.88	7.99	9.15	12.82	11.62
Fe <sub>2</sub> O <sub>3</sub> .....	0.59		1.41	1.29	2.21
FeO .....	4.11	3.35	4.12	3.37	5.30
MgO .....	1.86	1.54	3.04	2.21	1.92
CaO .....	0.68	1.10	2.84	1.82	5.89
Na <sub>2</sub> O .....	1.21	5.97	2.24	6.03	1.95
K <sub>2</sub> O .....	1.24	0.22	0.43	1.26	0.04
H <sub>2</sub> O + 110° C.	1.35	} 0.74	2.06	2.11	4.38
H <sub>2</sub> O - 110° C.	0.07		0.08	0.28	0.28
TiO <sub>2</sub> .....				0.60	0.17
MnO .....	trace			0.02	trace
P <sub>2</sub> O <sub>5</sub> .....				0.16	
Cr <sub>2</sub> O <sub>3</sub> .....					
CO <sub>2</sub> .....					
Total... ..	100.52	101.12	99.85	100.47	99.67

I. Quartz glaucophane schist, Four Mile Creek, Oregon; Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 53. Abundant quartz, some chlorite, pink garnets, considerable glaucophane, and muscovite.

II. Quartz glaucophane schist, Angel Island, San Francisco Bay; Ransome, analyst, *Bull. Dept. Geol. Univ. of California*, Vol. I., p. 231.

III. Quartz glaucophane schist, Little Harbor, Catalina Island; Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 48.

IV. Slightly altered sandstone, Sulphur Bank, California; Melville, analyst; G. F. Becker, Mon. XIII., U. S. Geol. Survey, p. 92. This is an arkose, slightly altered but has no glaucophane developed in it.

TABLE OF ANALYSES.

	VI. Albite Crossite Gneiss.	VII. Altered Diorite with Crossite and Lawsonite.	VIII. Soda Syenite Porphyry.	IX. Mica Glaucophane Schist.	X. Pseudodabase.
SiO <sub>2</sub> .....	65.2	61.55	67.53	58.26	51.27
Al <sub>2</sub> O <sub>3</sub> .....	15.8	17.28	18.57	16.21	15.04
Fe <sub>2</sub> O <sub>3</sub> .....	2.7	1.49	1.13	3.44	2.41
FeO .....	2.4	3.50	0.08	4.63	8.01
MgO .....	2.4	3.00	0.24	4.99	6.06
CaO .....	0.6	3.12	0.55	3.82	7.07
Na <sub>2</sub> O .....	10.8	8.47	11.50	5.36	4.43
K <sub>2</sub> O .....	0.1	0.07	0.10	0.39	0.12
H <sub>2</sub> O + 110° C.		1.21	0.31	0.98	} 3.34
H <sub>2</sub> O - 110° C.		0.12	0.15	0.22	
TiO <sub>2</sub> .....		0.28	0.07	1.37	1.33
MnO .....		trace		trace	0.25
P <sub>2</sub> O <sub>5</sub> .....			0.11		0.13
Cr <sub>2</sub> O <sub>3</sub> .....					
CO <sub>2</sub> .....					
Total .....	100.09	100.12	100.34	99.67	99.62

V. Lawsonite glaucophane gneiss, three miles southwest of Redwood; W. O. Clark, analyst. Abundant glaucophane and lawsonite, with a little garnet and white mica.

VI. Albite crossite gneiss, North Berkeley; H. Rosenbusch, *Sitzungsberichte d. k. Preuss. Akad.*, 1898, p. 712; calculated from the specific gravity of the rock, and the known composition of the two minerals that compose it, albite 75 per cent., and crossite 25 per cent.

VII. Slightly altered quartz diorite, Oak Ridge, five miles east of Calaveras Valley; W. O. Clark, analyst. Primary quartz, oligoclase, titaniferous hornblende, secondary crossite, lawsonite and titanite.

VIII. Soda syenite porphyry, Sierra Nevada, No. 1521 SN; Stokes, analyst, H. W. Turner, 17th An. Rept., Pt. I. (1896), p. 727.

IX. Mica glaucophane schist, Café Skarbeli, Syra, Grecian Archipelago; H. S. Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 39. This analysis shows a mica glaucophane schist of the composition of a diorite, and is introduced here for comparison with those from California.

X. Pseudodiabase, Sulphur Bank, California, No. 36, Sulphur Bank; Melville, analyst; G. F. Becker, Mon. XIII., U. S. Geol. Survey, p. 99. The rock analysed showed no glaucophane, but Becker mentions that mineral as being not uncommon in similar pseudodibases, which were thought to be altered sedimentary rocks.

TABLE OF ANALYSES.

	XI. Pseudodiorite.	XII. Glaucophane Schist.	XIII. Pseudodia- base.	XIV. Fourchite.	XV. Glaucophane Schist.
SiO <sub>2</sub> .....	50.44	49.68	49.08	46.98	47.84
Al <sub>2</sub> O <sub>3</sub> .....	8.18	13.60	14.68	17.07	16.88
Fe <sub>2</sub> O <sub>3</sub> .....	1.06	1.86	1.95	1.85	4.99
FeO.....	6.28	8.61	9.63	7.02	5.56
MgO.....	17.63	6.27	6.69	8.29	7.89
CaO.....	11.55	10.97	10.09	12.15	11.15
Na <sub>2</sub> O.....	2.98	3.09	4.60	2.54	3.20
K <sub>2</sub> O.....	0.56	0.12	0.20	0.53	0.46
H <sub>2</sub> O+110° C.	0.92	} 3.84	1.18	} 4.86	1.81
H <sub>2</sub> O-110° C.	0.07		0.28		0.17
TiO <sub>2</sub> .....		1.31	1.72		
MnO.....	0.21	0.04	0.15		0.56
P <sub>2</sub> O <sub>5</sub> .....		0.21	0.23	0.09	0.14
Cr <sub>2</sub> O <sub>3</sub> .....	0.48				
CO <sub>2</sub> .....					
Total.....	100.30	99.60	100.98	101.38	100.65

XI. Pseudodiorite, Knoxville, California No. 56, Knoxville; Melville, analyst; G. F. Becker, Mon. XIII., U. S. Geol. Survey, p. 101. This rock is a greenstone, composed almost entirely of actinolite, white mica, with rutile, zircon, and titanite. Becker does not mention glaucophane as occurring in this particular rock.

XII. Glaucophane schist, Sulphur Bank, No. 98 Sulphur Bank; Melville, analyst; G. F. Becker, Mon. XIII., U. S. Geol. Survey, p. 104. A basic glaucophane schist, with glaucophane, white mica, zoisite? (pale epidote?), albite, a little quartz, and titanite.

XIII. Pseudodiabase, Mt. St. Helena, California; No. 21 Coast Range; Melville, analyst; G. F. Becker, Mon. XIII., U. S. Geol. Survey, p. 98. A little altered igneous rock, with fresh plagioclases, some uraltite, zoisite? (pale epidote?), and a little actinolite.

XIV. Fourchite, Angel Island; Ransome, analyst, *Bull. Dept. Geol. Univ. of California*, Vol. I., p. 231. A diabase dyke, slightly altered, with some secondary glaucophane.

XV. Garnet glaucophane schist, Pine Canyon, Mt. Diablo, California; Melville, analyst; H. W. Turner, *Bull. Geol. Soc. Amer.*, Vol. II. (1891), p. 413.

TABLE OF ANALYSES.

	XVI. Garnet Glauco- phane Schist.	XVII. Epidote Glauco- phane Schist.	XVIII. Eclogite.	XIX. Epidote Glauco- phane Schist.	XX. Albite.
SiO <sub>2</sub> .....	49.15	46.07	44.15	42.59	67.09
Al <sub>2</sub> O <sub>3</sub> .....	15.87	15.35	10.18	} 31.00	20.47
Fe <sub>2</sub> O <sub>3</sub> .....	4.10	3.61	11.92		
FeO .....	7.75	9.87	13.04		
MgO .....	7.53	7.83	6.18		
CaO .....	9.06	4.37	4.51	5.10	
Na <sub>2</sub> O .....	3.59	3.22	5.11	10.80	0.24
K <sub>2</sub> O .....	0.54	2.68	2.09	4.16	10.96
H <sub>2</sub> O + 110° C.	1.07	4.25	} 0.95	1.01	
H <sub>2</sub> O - 110° C.	0.16	0.16		} 5.34	0.59
TiO <sub>2</sub> .....	1.19	1.63	trace		0.27
MnO .....	trace	trace			
P <sub>2</sub> O <sub>5</sub> .....					
Cr <sub>2</sub> O <sub>3</sub> .....					
CO <sub>2</sub> .....		1.05			
Total .....	99.84	100.09	99.31	100.00	99.62

XVI. Garnet glaucophane schist, Tupper Rock, near Brandon, Oregon; Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 53. Abundant glaucophane, and garnets, with some epidote, zoisite, and white mica.

XVII. Epidote glaucophane schist, Roseburg, Oregon; Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI. (1901), p. 53. Abundant glaucophane, epidote, and muscovite, with a few quartz grains.

XVIII. Omphacite eclogite, Coyote Creek, six miles north of San Martin, California; C. B. Allen analyst; R. S. Holway, *Jour. Geol.*, Vol. XII., p. 356. A massive rock composed of omphacite, garnet, white mica (muscovite), actinolite, titanite, and rutile.

XIX. Epidote glaucophane schist, North Berkeley, California; H. Rosenbusch, *Sitzungsberichte, K. Preuss. Akad. Wiss.*, 1898, p. 716. A partial analysis, with an estimate of the other components.

XX. Albite, from glaucophane schist, San Pablo, California; W. C. Blasdale, analyst, *Bull. Dept. Geol. Univ. of California*, Vol. II., p. 343.

XXI. Pargasite, from the pargasite eclogite, Arroyo Hondo, at the northern end of Calaveras Valley, Santa Clara County, California; W. O. Clark, analyst.

XXII. Glaucophane, from glaucophane schist, San Pablo, California; W. C. Blasdale, analyst, *Bull. Dept. Geol. Univ. of California*, Vol. II., p. 338.

XXIII. Glaucophane, from glaucophane schist, San Pablo, California; W. C. Blasdale, analyst, *loc. cit.*

XXIV. Crossite, from albite crossite gneiss, North Berkeley; W. S. T. Smith, analyst, in C. Palache, *Bull. Dept. Geol. Univ. of California*, Vol. I., p. 188.

TABLE OF ANALYSES.

	XXI. Pagasite.	XXII. Glaucophane.	XXIII. Glaucophane.	XXIV. Crossite.	XXV. Glaucophane.
SiO <sub>2</sub> .....	42.68	54.52	52.39	55.02	57.67
Al <sub>2</sub> O <sub>3</sub> .....	9.96	9.25	11.29	4.75	11.07
Fe <sub>2</sub> O <sub>3</sub> .....	6.12	4.44	3.74	10.91	3.20
FeO.....	12.25	9.81	9.13	9.46	9.68
MgO.....	9.58	10.33	11.37	9.30	9.85
CaO.....	11.83	1.98	3.03	2.38	0.95
Na <sub>2</sub> O.....	3.30	7.56	6.14	7.62	6.80
K <sub>2</sub> O.....	0.89	0.16	trace.	0.27	0.42
H <sub>2</sub> O+110° C.	3.16	1.78	2.57		0.36
H <sub>2</sub> O—110° C.	0.12				0.12
TiO <sub>2</sub> .....	0.68	0.39	0.14		
MnO.....	trace	0.46	trace	trace .	0.06
P <sub>2</sub> O <sub>5</sub> .....					
Cr <sub>2</sub> O <sub>3</sub> .....					
CO <sub>2</sub> .....					
Total.....	100.57	100.68	99.80	99.70	100.18

XXV. Glaucophane from Syra, Greece; Washington, analyst, *Amer. Jour. Sci.*, IV. Ser., Vol. XI., p. 40.

XXVI. Actinolite, Berkeley, California; W. C. Blasdale, analyst, *Bull. Dept. Geol. Univ. of California*, Vol. II., p. 333.

XXVII. Actinolite, San Pablo, California; W. C. Blasdale, analyst, *loc. cit.*

TABLE OF ANALYSES.

	XXVI. Actinolite.	XXVII. Actinolite.	XXVIII. Chlorite.	XXIX. Talc.	XXX. Zoisite?
SiO <sub>2</sub> .....	55.21	55.56	27.38	56.02	39.80
Al <sub>2</sub> O <sub>3</sub> .....	3.45	2.05	26.15	9.02	22.72
Fe <sub>2</sub> O <sub>3</sub> .....			0.78	1.10	4.85
FeO.....	7.49	5.97	12.70	5.14	1.49
MgO.....	18.97	19.45	18.92	24.10	3.89
CaO.....	10.50	12.13		0.60	17.55
Na <sub>2</sub> O.....	2.45	1.94	1.15		4.09
K <sub>2</sub> O.....		0.30			0.12
H <sub>2</sub> O+110° C.	1.75	2.58	11.44	4.34	5.25
H <sub>2</sub> O—110° C.			1.51	0.16	
TiO <sub>2</sub> .....					trace
MnO.....					0.26
P <sub>2</sub> O <sub>5</sub> .....					
Cr <sub>2</sub> O <sub>3</sub> .....					
CO <sub>2</sub> .....					
Total.....	99.82	99.98	100.03	100.48	100.02



XXVIII. Chlorite from glaucophane schist, San Pablo, California; W. C. Blasdale, analyst, *Bull. Dept. Geol. Univ. of California*, Vol. II., p. 340.

XXIX. Talc, from glaucophane schist, San Pablo, California; W. C. Blasdale, analyst, *loc. cit.*

XXX. Zoisite (or pale epidote?), from pseudodiabase; Melville, analyst; G. F. Becker, Mon. XIII., U. S. Geol. Survey, p. 79.

TABLE OF ANALYSES.

	XXXI. Garnet.	XXXII. Lawsonite.
SiO <sub>2</sub> .....	38.69	38.45
Al <sub>2</sub> O <sub>3</sub> .....	19.10	31.35
Fe <sub>2</sub> O <sub>3</sub> .....		0.86
FeO.....	26.81	0.10
MgO.....	5.07	0.17
CaO.....	10.64	17.52
Na <sub>2</sub> O.....		0.06
K <sub>2</sub> O.....		0.23
H <sub>2</sub> O+110° C.....		11.21
H <sub>2</sub> O-110° C.....		
TiO <sub>2</sub> .....		0.38
MnO.....		trace
P <sub>2</sub> O <sub>5</sub> .....		
Cr <sub>2</sub> O <sub>3</sub> .....		
CO <sub>2</sub> .....		
Total.....	100.31	100.33

XXXI. Garnet, from omphacite eclogite, Coyote Creek, six miles north of San Martin, Santa Clara County, California; W. O. Clark, analyst.

XXXII. Lawsonite from glaucophane eclogite, Reed's Station, Tiburon Peninsula, California; Schaller and Hillebrand, analysts, *Amer. Jour. Sci.*, IV. Ser., Vol. XVII. (1904), p. 197.

### SUMMARY.

Glaucophane-bearing rocks have been made out of very different original materials. Siliceous fragmental sediments, deposits of organic silica, acid arkoses, medium basic clay shales, and basic tuffs have all been altered to a somewhat similar product. And igneous rocks have contributed to a like result. Syenites, diorites, diabases and gabbros, and probably pyroxenites have been changed into glaucophane schists. At first sight it would seem a hopeless task to attempt to find out the origin of a glaucophane schist when it might have been made from any one of these rocks. But, fortunately, the intrinsic character of the original rock has not been altered, and the chemical readjustment consequent upon metamor-

phism has done nothing more than change the mineralogical association. Each sort of rock, whether igneous or sedimentary, has its own peculiar chemical composition, and this is disclosed by a chemical analysis, no matter what molecular readjustment has taken place. Metamorphism was once considered as a sort of magical process by which almost any sort of rock might be made out of any sort of material. But metamorphism such as we have to deal with in the glaucophane-bearing rocks of the Coast Ranges may be defined merely as recrystallization. A siliceous rock remains siliceous, a basic ferruginous or magnesian rock remains ferruginous or magnesian. Little is added and little is taken away, not enough in any case to obscure the relations of the original material and the recrystallized product. The only essential difference is the water of constitution, which is always present in some mineral in the recrystallized rocks.

Analyses I., II. and III. in the foregoing table are of altered siliceous sediments, and are clearly recognizable as such by their chemical composition. Analysis IV. is of an arkose which corresponds closely to a granodiorite. No. V. is a lawsonite gneiss, with every mineral in it a product of recrystallization, but its chemical constitution shows it to have been originally either a quartz diorite or an arkose from such a rock. Analysis VI. is an albite crossite gneiss, with every mineral of secondary origin, but chemically it is a soda syenite, and it was originally such an igneous rock or an arkose from a soda syenite. No. VIII. is a soda syenite porphyry, showing a composition almost identical with No. VI., and glaucophane-like minerals have been observed at several places in the Sierra Nevada in dynamically altered soda syenites.

No. VII. is a little altered quartz diorite in which secondary lawsonite and crossite have been developed by dynamic metamorphism.

No. IX. is a mica glaucophane schist, but the chemical composition shows it to have been a normal diorite.

Nos. X., XI., XIII. and XIV. are of metamorphosed medium basic rocks, either diabases or gabbros, and the chemical composition shows only the addition of water, otherwise they are still gabbros in composition.

Nos. XII., XV., XVI., XVII. and XIX. are basic glaucophane schists, but the chemical analyses show them to have been gabbros or diabases.

No. XVIII. is a massive eclogite, composed of garnet, omphacite actinolite, glaucophane, white mica and titanite, but the chemical analysis shows it to have been a basic gabbro or even possibly a pyroxenite. No rocks of the chemical nature of peridotite have been discovered by chemical analysis among the glaucophane schists, but some of the actinolite chlorite schists would probably show such a constitution.

These results all show that there is no need of supposing that magnesian or alkaline or siliceous solutions have permeated the altered rocks, adding one substance and taking away another. The small amounts of mechanically contained water in all the sediments, and the water disseminated through all the cracks in the igneous rocks have been sufficient, when heated under pressure, to produce all the phenomena of recrystallization seen in the Coast Ranges. This small amount of water would not have been sufficient to produce aqueo-igneous fusion, nor is it likely that this condition was ever reached, for the minerals were not all crystallized at the same time. But each molecule of water, with almost unlimited time, could accomplish a great deal of work, and this work was not finished until that molecule was fixed as water of constitution in some mineral.

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